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Technical Report

No. 13161

FABRICATION AND TESTING OF A CERAMIC

TWO-CYCLE DIESEL ENGINE

CONTRACT DAAE07-83-C-R05B

DECEMBER 1986

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The project effort was focused around evaluating the friction horsepower performance of a single cylinder, two-stroke opposed piston diesel engine, fabricated from conventional metal components and then with the substitution of ceramic components for the cylinder liner and pistons. The ceramic configurations were run ringless and without cylinder lubrication. Frictional torque measurements were 50% lower than in the standard baseline case.

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PREFACE

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1.0. INTRODUCTION

This technical report summarizes work performed by Sohio Engineered Materials Company, formerly The Carborundum Company and its subcontractors, Ricardo Consulting Engineers and DHR, Inc. investigating the use of ceramic materials for diesel engine technology. The work was performed for the Department of Defense (DOD) and administered by the U.S. Army Tank-Automotive Command (TACOM) under Contract No. DAAE07-83-C-R058. This is the final report covering the period September 21, 1983 through April 30, 1985.

2.0. OBJECTIVE

The objective of the 18 month program was to evaluate and demonstrate the potential benefits of a range of ceramic materials for diesel engine technology, and increase the experience baseline for component fabrication, product reliability and nondestructive evaluation (NDE).

The program consisted of three basic tasks:

- Task I - Manufacture Prototype Ceramic Components
- Task II - Conduct Single Cylinder Rig Tests
- Task III - Demonstrate Product Reliability

The project effort was focused around evaluating the friction horsepower performance of a single cylinder, two-stroke, opposed piston diesel engine fabricated from conventional metal components, and with the substitution of ceramic components for the cylinder liner and pistons. Figure 2-1 shows the planned work schedule. The key milestones for this program were as follows:

(1) To conduct baseline studies on a metal engine;

(2) Perform thermal and stress analyses for various ceramic material designs;

(3) Design and fabricate alternative ceramic materials;

(4) Perform preliminary ceramic engine evaluations;

(5) Select optimum ceramic component materials;

(6) Perform engine durability tests (goal 100 hours);

(7) Multiple fabrication of pistons by injection molding;

(8) Nondestructive evaluation of piston quality.

PROGRAM: Fabrication and Testing of a Ceramic Two-Cycle Diesel Engine
CONTRACTOR: Standard Oil Engineered Materials Company
CONTRACT NO: DAAE07-83-C-R058

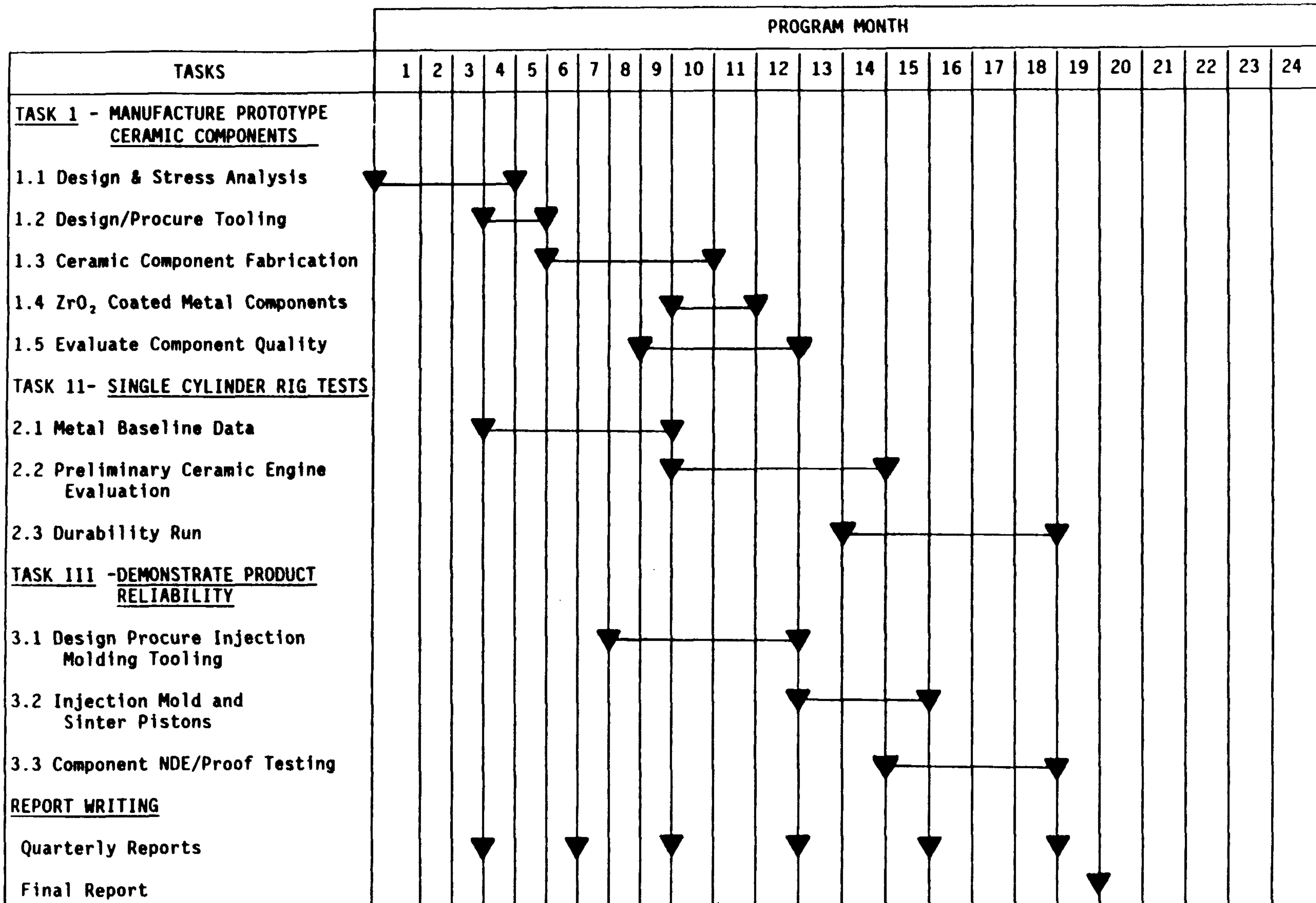


Figure 2-1. Planned Work Schedule

3.0. CONCLUSIONS

- Sintered alpha silicon carbide (SASC) or sialon pistons in a sintered alpha silicon carbide cylinder liner can achieve sustained operation at partial engine load without cooling and without lubrication.

- Ringless ceramic pistons with close cylinder-to-piston clearance can be operated in a diesel engine and achieve adequate compression pressure for ignition.

- Ringless ceramic pistons without cylinder lubrication exhibited up to 50% lower frictional torque compared to conventional metal components with lubrication.

- Sintered alpha silicon carbide and sialon pistons exhibited similar reduction in friction over conventional metal components.

- Ceramic component failures were concluded to be a result of limitations in component design.

- The identified cause of ceramic component failure was attributed to piston seizure and resulting tensile stresses causing fracture.

- Further evaluation of component design, dimensional constraints and thermal stress conditions is required to demonstrate the durability and full potential of ceramic components at high engine load.

- NDE by the acousto-optic technique of producing a nonspecular reflection profile requires further development before its usefulness to detect surface flaws in alpha silicon carbide can be assessed.

- Several good pistons were fabricated and passed X-ray inspection, however, further development is required in tooling design and processing to establish mass fabrication capability of sintered alpha silicon carbide piston components by injection molding.

4.0. RECOMMENDATIONS

4.1. Piston Design

The piston geometry should be redesigned to include a tapered profile in the crown area to compensate for the radial expansion of the crown, thereby maintaining adequate piston-to-cylinder clearance at full load operating temperatures.

The top of the piston should be provided with an insulative coating or insert to reduce heat transfer during combustion and reduce the magnitude of radial expansion of the crown.

4.2. Cylinder Design

Further thermal analysis of the ceramic cylinder design should be undertaken to evaluate the dimensional changes that will occur under severe operating conditions.

Selective insulation of the cylinder should be investigated to allow more uniform heat up along the cylinder length and maintain better uniformity in piston-to-cylinder clearance.

4.3. Further Recommendations

Improved piston/carrier assembly designs should be investigated to simplify and improve the reliability of the attachment of the ceramic piston to the metal connecting rod. A potential improved assembly might incorporate a floating ceramic wrist pin with a spherical bearing surface, thereby allowing complete piston alignment.

5.0. DISCUSSION

5.1. Background

The engine used for the contract work was based on a design by Professor Seamus Timoney of the University College Dublin (UCD) in Ireland. The engine is a horizontally opposed piston, two-stroke single cylinder diesel with variable compression ratio.

In Professor Timoney's early investigations catastrophic failures occurred using various ceramic materials including glass ceramics and reaction bonded silicon nitride.

In 1982, the Sohio Engineered Materials Company successfully ran, in this engine setup, a ceramic cylinder assembly and pistons made from sintered alpha silicon carbide. A photograph of the ceramic engine is shown in Figure 5-1.

The objective was to demonstrate an improvement in engine performance over that using metals through higher operating temperatures with ceramics.

A significant finding was a reduction in engine friction utilizing ringless pistons (empty ring grooves), and without cylinder cooling or lubrication. These very interesting initial results with silicon carbide components prompted making a new cylinder and pistons with reduced piston-to-cylinder clearance. The closer fitting pistons made without ring grooves resulted in an even further reduction in friction horsepower. This work was reported at the 1983 SAE International Congress.[1]

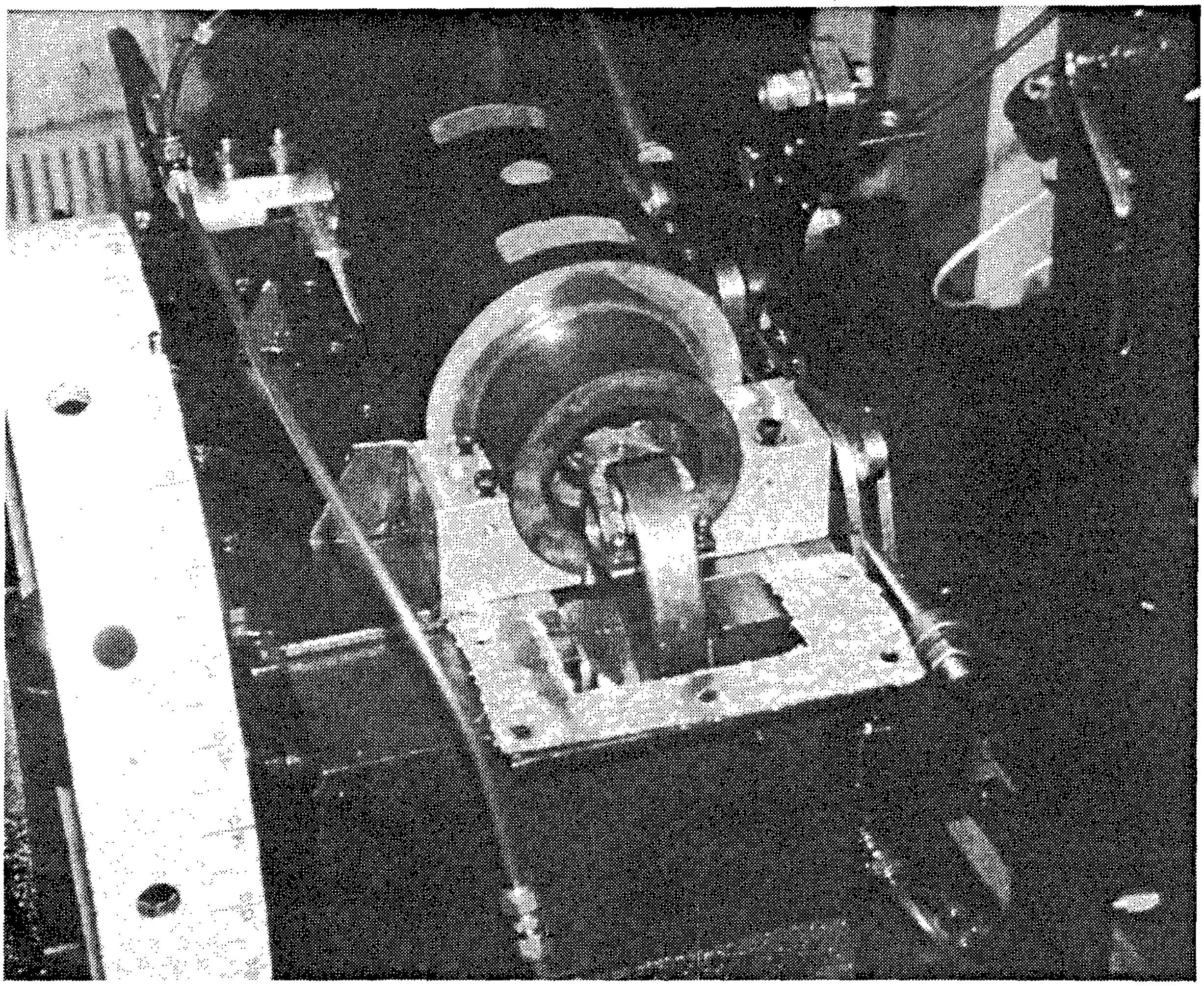


Figure 5-1. Engine Setup at the University College Dublin with SASC Components

This contract effort was initiated after relocating and reconditioning the UCD single cylinder engine at the Eaton Corporation, Engineering & Research Center, Southfield, Michigan.

5.2. Engine Design

The opposed piston engine with variable compression ratio offers many practical advantages where the application of ceramic materials are under consideration. A schematic of the engine is shown in Figure 5-2.

The rocker arm geometry is designed to give minimum piston side thrust on the cylinder wall. This reduces the tribology problems at the piston-cylinder interface. The opposed piston configuration allows each piston to serve as the cylinder head for its counterpart, thus eliminating the head gasket, and hold-down fasteners. Inlet and exhaust ports within the cylinder eliminates the need for valves greatly simplifying the combustion chamber geometry. Additionally, use of the two-stroke cycle eliminates force reversals and resulting tension on the piston and rod connection. This last point makes the design ideal for investigating ceramics, due to their lower tensile strength compared to metals.

The engine design specifications are shown in Table 5-1.

Table 5-1. Engine Design Specifications

Specification	Value
Volumetric Displacement, liters	0.54
Cylinder Bore Diameter, in.	2.750
Stroke, in.	2.815
Rated power at 2400 rpm (estimated), HP	11-12

5.3. Materials Selection and Testing

The ceramic materials considered for component fabrication and testing in this program were:

- sintered alpha silicon carbide (SASC)
- partially stabilized zirconia (PSZ) - as a substitute for ZrO_2 coated metal components
- sialon
- fine grained SASC/Si composite
- SASC/solid lubricant composite

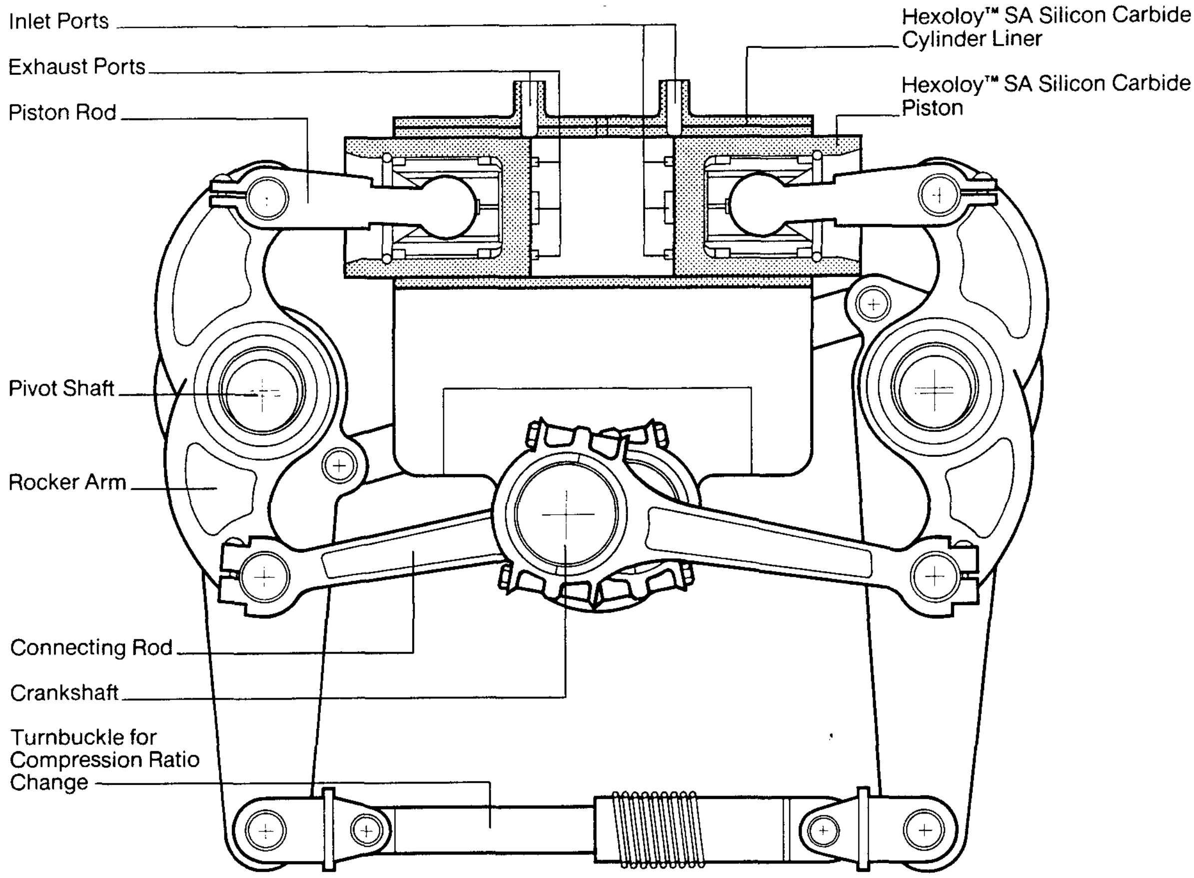


Figure 5-2. Schematic of the Horizontally Opposed Single Cylinder Diesel Engine

The final material combinations selected for component fabrication and experimentation within the engine were the following:

- SASC cylinder and pistons
- SASC cylinder and sialon pistons
- PSZ cylinder and pistons

The PSZ cylinder and pistons were ultimately unable to be included in actual engine tests due to late vendor deliveries. After review with TACOM personnel, the fine grained SASC/Si composite and SASC/solid lubricant composite from the initial materials candidate list were evaluated within a parallel, but separate SOHIO funded program with DHR, Inc. and Pennsylvania State University (PSU).

Selected properties, for comparative purposes, of the principal material candidates are shown in Table 5-2. Further detail on material properties characterization is presented in Appendix H.

Table 5-2. Properties of Selected Materials

PROPERTY	SASC*	Sialon+	PSZ++
Density, gms/cc	3.14	3.24	5.73
Flexual Strength, 500°C 4 point, psi x 10^3	55.0	89.6	66.2
Modulus of Elasticity, RT, psi x 10^6	59	41	30
Thermal Expansion coefficient, RT-700°C, cm/cm/°C/10^6	4.0	3.4	10.6
Thermal Conductivity, RT, W/m°K	125	20	2

* SOHIO Engineered Materials Company, SA-80
\+ Hitachi Ltd., Sialon 102
++ NILCRA Ceramics (USA) Inc., MS Grade

5.4. Ceramic Component Design

The initial SASC cylinder assembly consisted of two sintered alpha silicon carbide cylinders joined together forming an inner liner with 8 exhaust and

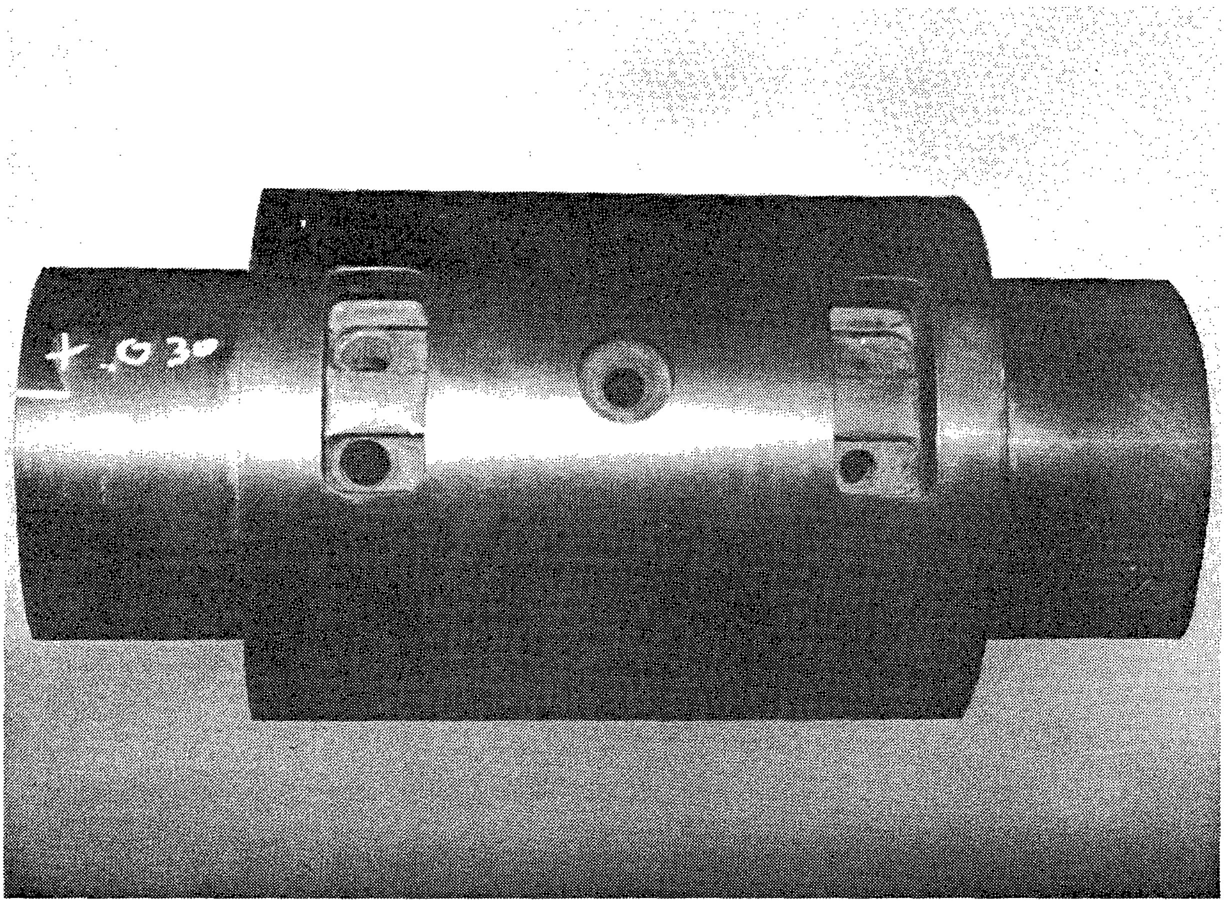


Figure 5-3. SASC Cylinder Assembly (Initial Design)

8 inlet ports either side of a single injector hole. Two annular cavities in the outer housing form the exhaust and inlet manifolds shown in Figure 5-3 and schematic drawings in Appendix A.

The initial design of the piston carrier attachment was a ball end connecting rod and matching socket assembly in the piston shown in Figure 5-4. The piston has no ring grooves, but relies on tight tolerances with the cylinder inside diameter for sealing.

The piston assembly consists of the ceramic piston fitting over a split steel carrier with spherical sockets retaining the ball end. The carrier and ball end rod assembly are held in the piston cup by a split retainer ring epoxied in the groove at the lower end of the skirt. This initial design was judged as inadequate based on two piston skirt failures from preliminary testing. An example of the piston failure is shown in Figure 5-5.

Consequently, the piston carrier attachment was redesigned with an SASC carrier and a floating metal wrist pin shown in drawings in Appendix A.

5.5. Engine Testing

5.5.1. Engine Build B/N-01. The metal engine as delivered from the University College Dublin (UCD) required balancing and reconditioning due to oil leaks and worn components. Precontract testing was performed to reverify friction results measured at UCD.

The exhaust side connecting rod was fitted with a strain gage and the leads connected to a readout at the control console so that the operator could shut the engine down if significant tension was observed in the connecting rod. Lucite end covers were installed to provide visual monitoring of the rods and rockers during operation. The final assembly shown in Figure 5-6 was completed November 11, 1983.

The engine was motored to 1,000 RPM with the strain gage indicating a compression pressure of 280 psi. After bleeding the injector lines the engine was fired. Combustion was poor, however, ignition was sustained. After 20 minutes of firing an audible crack was heard and the engine was immediately shut down. Prior to shut down the intake air thermocouple showed the temperature increased from 88°F to 187°F.

Despite the failure, the engine could be turned over freely by hand, enabling the rocker pins to be removed without difficulty. The pistons suffered slight damage at the ends as shown in Figure 5-7, and both piston carriers were cracked. Further inspection revealed the cylinder had failed as shown in Figure 5-8, and the engine was completely dismantled.

Further inspection of the cylinder failure, and review of inlet air temperature data indicated the cylinder failure permitted short circuiting of exhaust gas to the inlet, accounting for the temperature rise on the intake side.

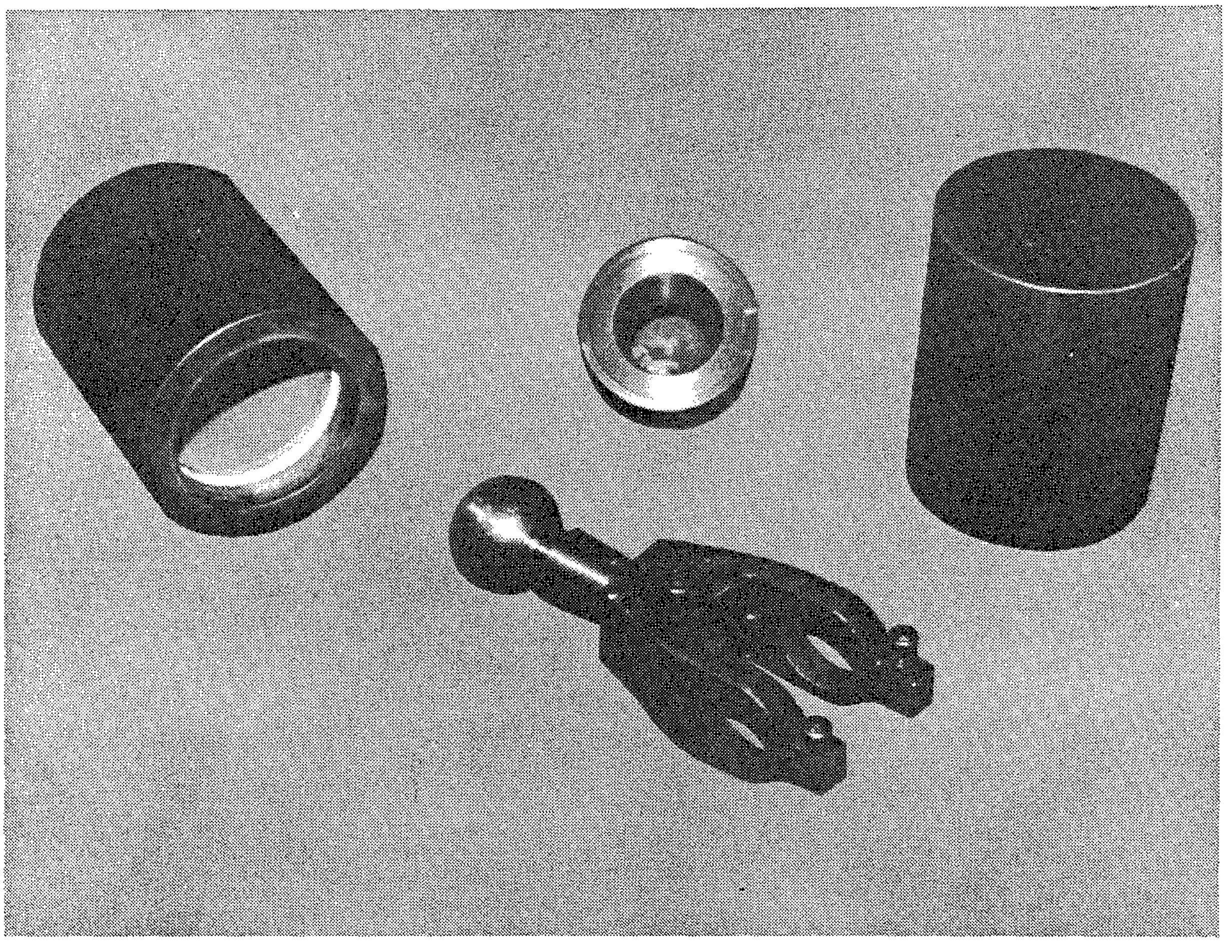


Figure 5-4. SASC Pistons with Ball and Socket Connecting Rod

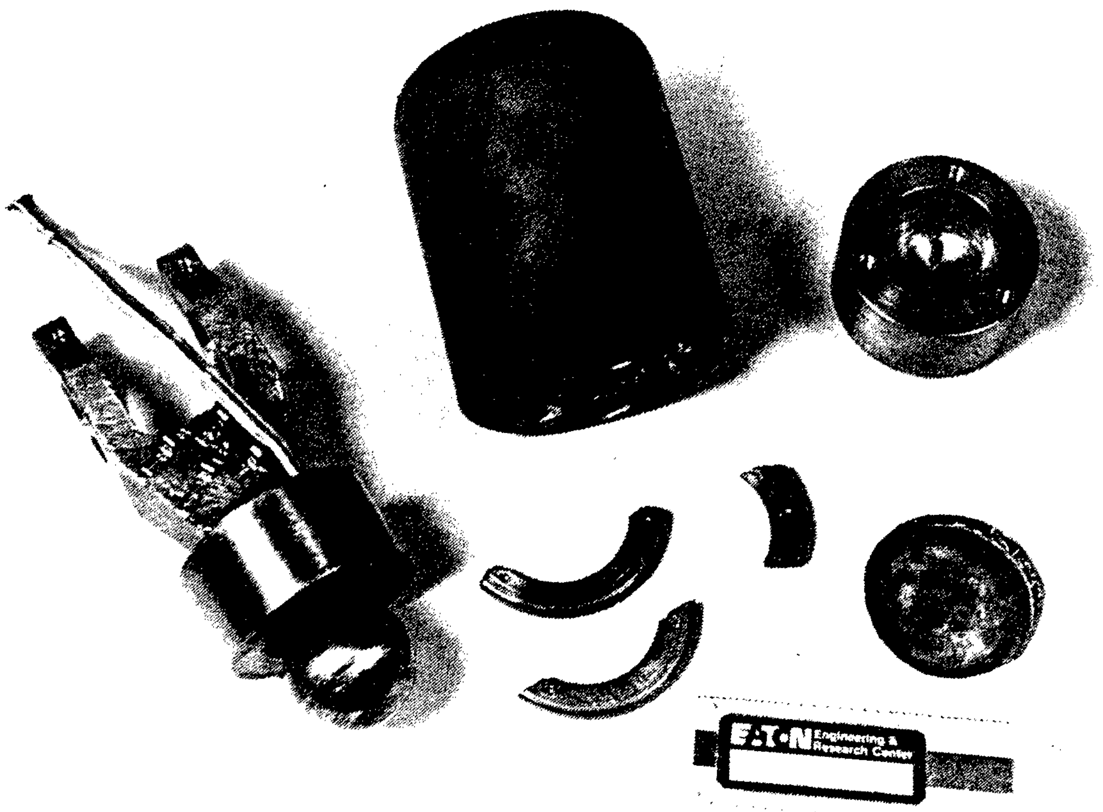
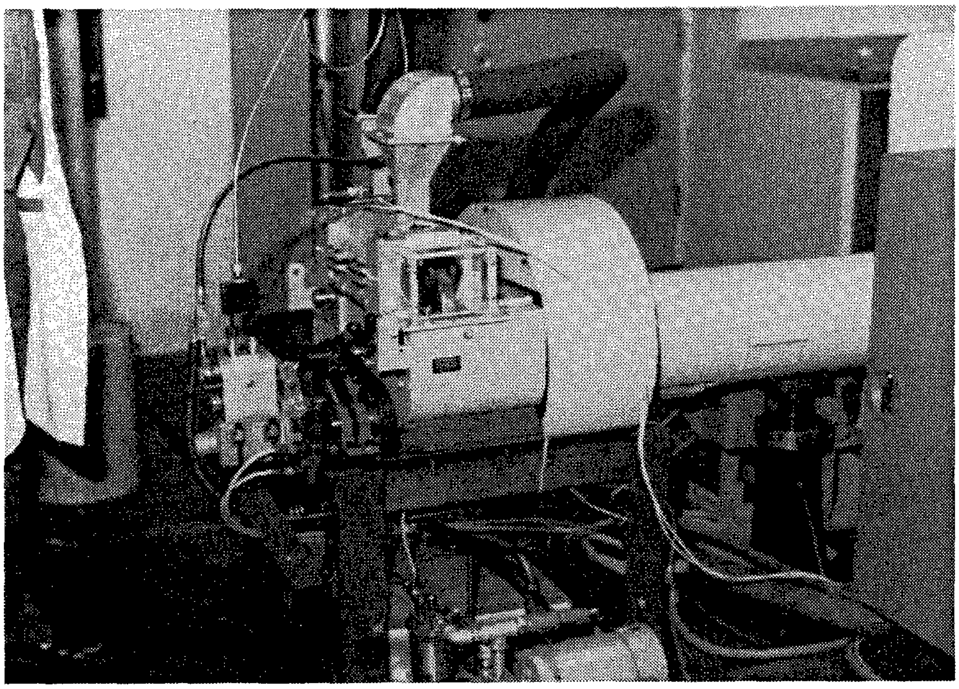
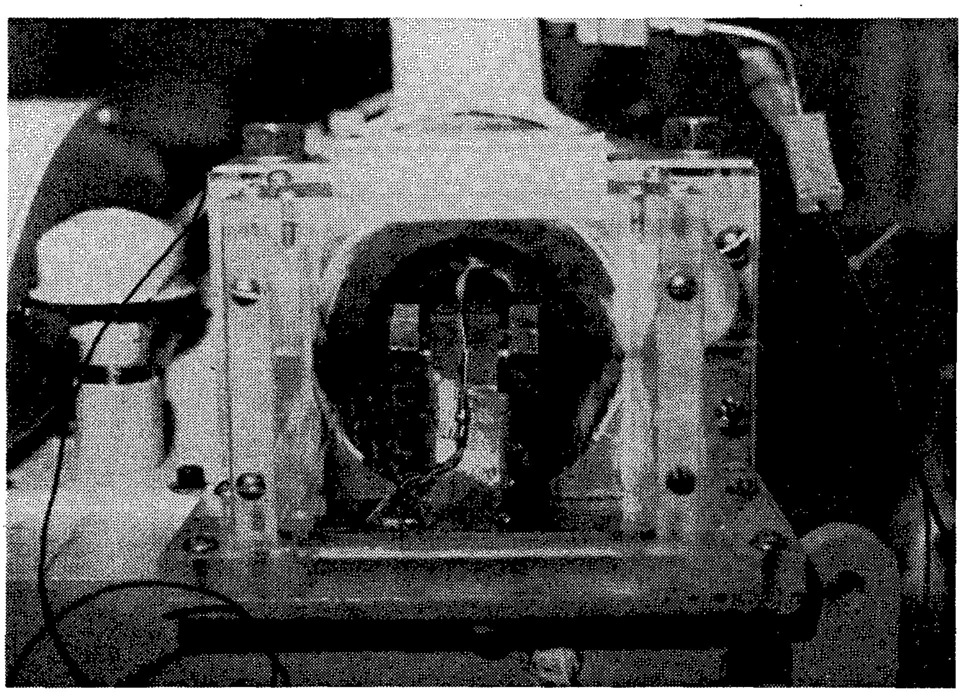


Figure 5-5. SASC Piston Skirt Fracture



(a) Overall View



(b) Cylinder End View

Figure 5-6. Engine Setup at Eaton Corporation

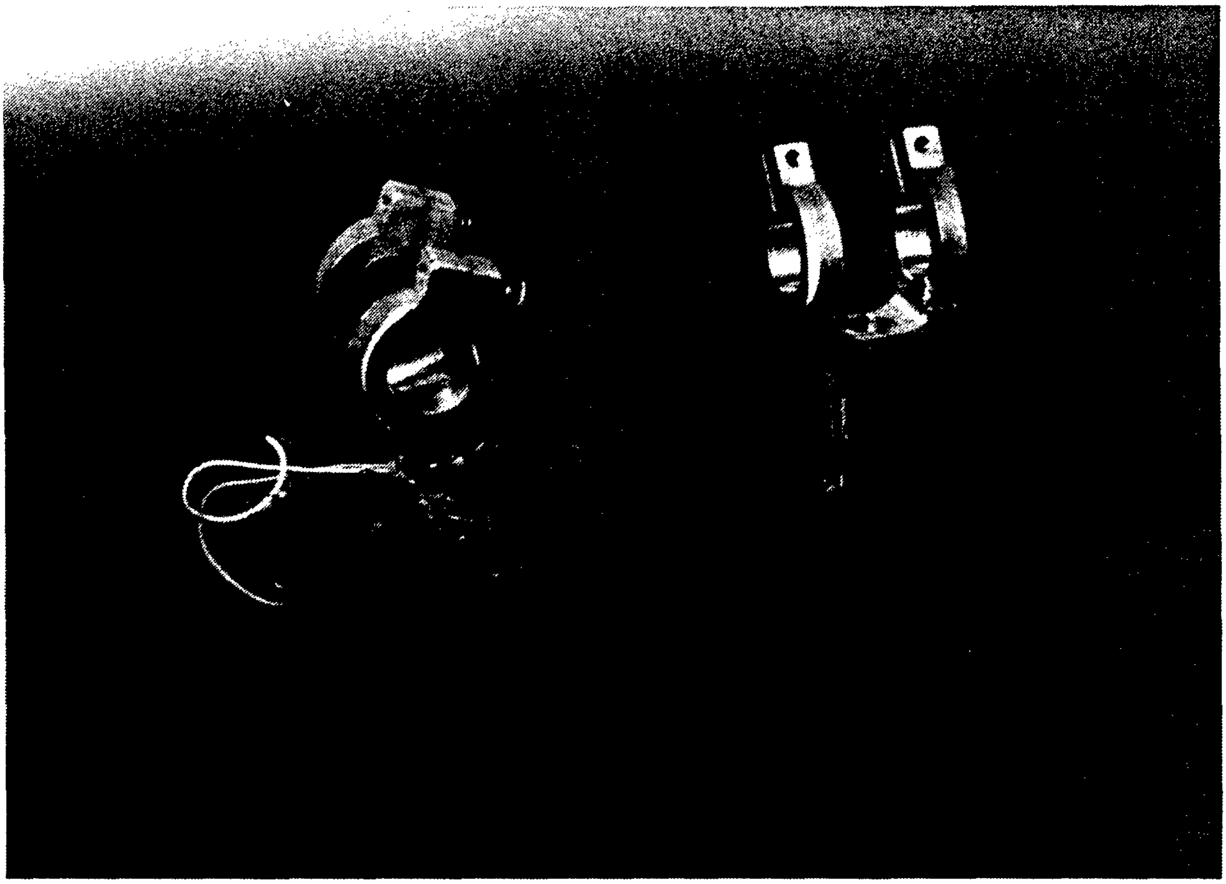
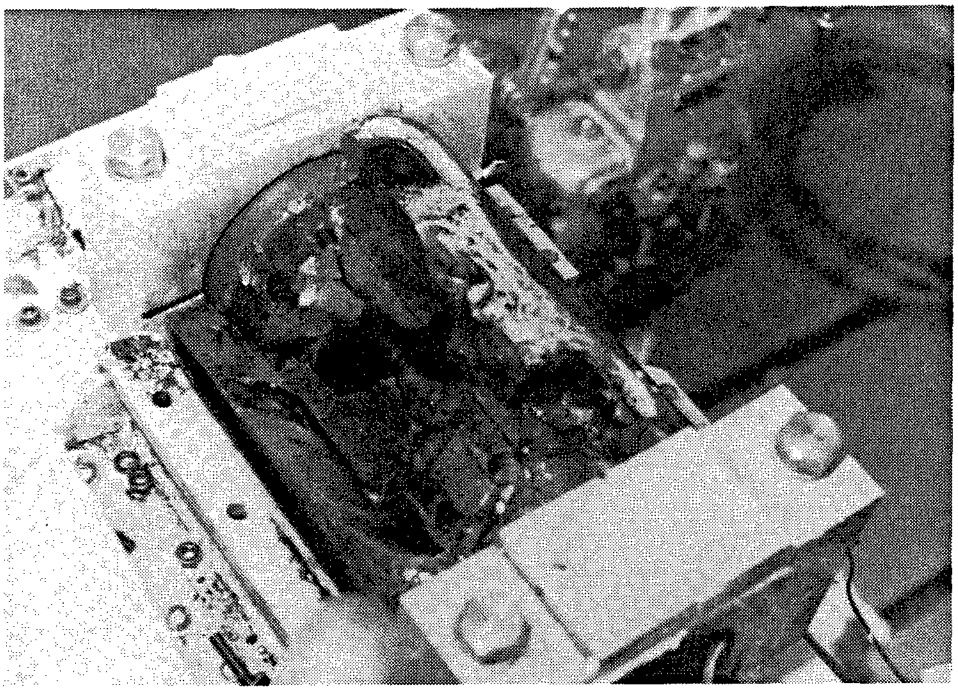
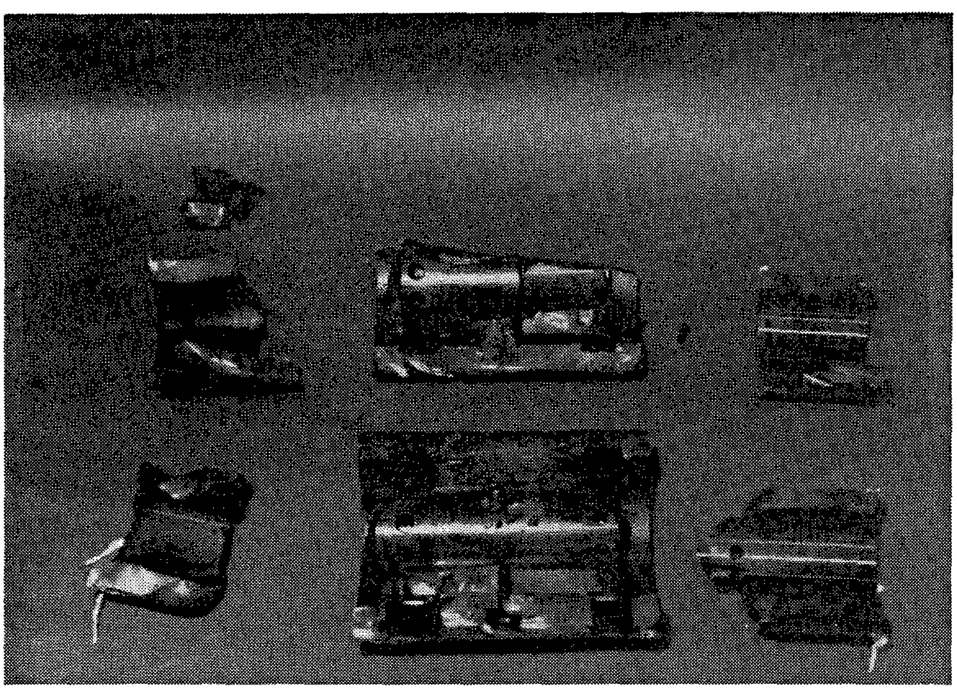


Figure 5-7. SASC Piston Damage (B/N-01)



(a) Fractured Cylinder in Engine



(b) Fractured Cylinder Segments

Figure 5-8. SASC Cylinder Failure (B/N-01)

The probable failure origin was identified in the outer housing at the interface of the liner and outer housing, near the injector port. Appendix B details the fractography analysis and conclusions. The exact reason for the failure was undetermined, however, the presumed probable cause was residual tensile stresses due to the method of joining.

Based on the postmortem and at the recommendation of the project engineer, a redesign of the cylinder liner, and further modification to the piston carrier assembly was initiated.

Table 5-3. Engine Build (B/N-01) and Results

Components	Identification	Remarks
SASC Cylinder Liner and Housing	C/N-00	Original assembly from UCD tests
SASC Pistons	P/N-1 and 2	Modified carrier design - SASC carrier with floating metal wrist pin

<u>Operating Results</u>
Engine Motoring - 9.2 hrs.
Engine Firing - 0.3 hrs.

<u>Remarks</u>
Cylinder liner/housing assembly fractured November 11, 1983

Cumulative Operating Time:

	Motoring/Firing Combined (Hrs.)	Firing (Hrs.)
. Cylinder Liner/Housing Assembly*	70.6	41.3
. Pistons	9.2	0.3

Pistons sustained chipping damage on the skirt bottom

Build Date: November 11, 1983

*Includes previous test history:
University College Dublin -
Engine Motoring - 16.5 Hrs.
Engine Firing - 32 Hrs., maximum engine speed 1,800 rpm

Eaton Corporation -
Engine Motoring - 10 Hrs.
Engine Firing - 9 Hrs., maximum engine speed 1,600 rpm
Piston skirt fracture below retainer ring groove

5.5.2. Engine Build B/N-02. Preliminary engine running and retesting with the metal engine resulted in piston ring and piston land damage due to excessive piston-to-cylinder clearance and combustion shock.

The injector line was modified with flats for strain gage installation to provide a sharper injector pressure signal. Normal injector opening pressure was 3,100 psi.

Table 5-4. Engine Build B/N-02 and Results

Components	Identification	Remarks
Cast Iron Cylinder	-	Original Timoney metal components with aluminum water jacket for cylinder cooling.
Aluminum Pistons with Cast Iron Rings	-	.030 in. piston-to-cylinder clearance, excessive.
<u>Operating Results</u>		
Preliminary Operation Engine Motoring - 2.5 Hr. Engine Firing - .5 Hr.		Poor combustion, excessive blowby, insufficient intake air, compression pressure 390 psi at 250 rpm. Engine driven roots blower added - 2/3/84
Retest (February 8, 1984) with blower Engine Motoring - 8.25 Hr. Engine Firing - 1 Hr.		5 HP at 1,600 rpm.
Component Inspection February, 1984		Second Compression ring and piston ring land damaged, injector nozzle damage.
Build Date: January 24, 1984		

5.5.3. Engine Build B/N-03. A new set of aluminum pistons were made by the Eaton Corporation machine shop with a 0.005 inch piston-to-cylinder design clearance. Standard commercial Briggs and Stratton piston rings were installed.

Operation of the engine with new pistons and rings improved compression pressure and eliminated blow-by. The engine was demonstrated for TACOM personnel February 23, 1984. Friction horsepower measurements were obtained for the engine without connecting rods and pistons attached. The hot friction curve for the full engine assembly is shown in Figure 5-9.

The metal engine evaluation program was initiated and operating characteristics recorded. During this testing on March 12, 1984, the engine lost power due to a failure of the intake rocker arm, shown in Figure 5-10.

The exhaust rocker and connecting rods were given a Magnaflux inspection, revealing numerous small cracks. After calculating the working stresses, fabrication of new rockers and connecting rods from steel was recommended.

Table 5-5. Engine Build B/N-03 and Results

Components	Identification	Remarks
Cast Iron Cylinder	-	No change from B/N-02
New Aluminum Pistons, New Rings	-	Pistons made at Eaton, commercial Briggs and Stratton cast iron rings.
Operating Results		
Engine Evaluation Accumulated Time: - Engine Motoring - 4.7 Hrs. - Engine Firing - 11.5 Hrs.		Peak compression pressure 900 psi at 2000 rpm, 5.52 BHP, BSFC-1.02. LB./HP-HR.
Inspection of Pistons/Rings		Good condition.
Continued Engine Testing March 12, 1984		Lost engine power, intake rocker arm failure at the connecting rod journal.
Build Date: February 22, 1984		

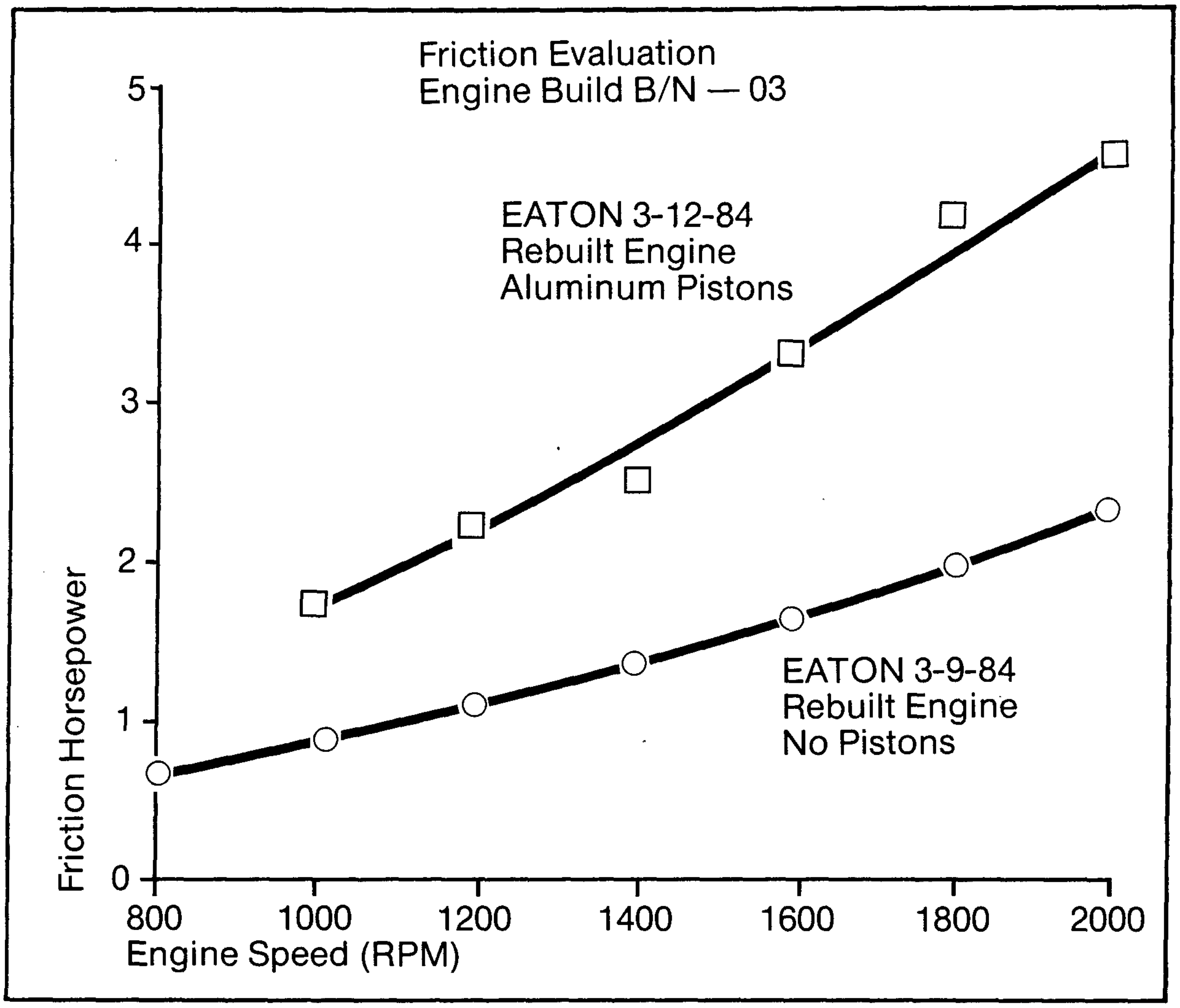


Figure 5-9. Friction Evaluation for Metal Engine (B/N-03)

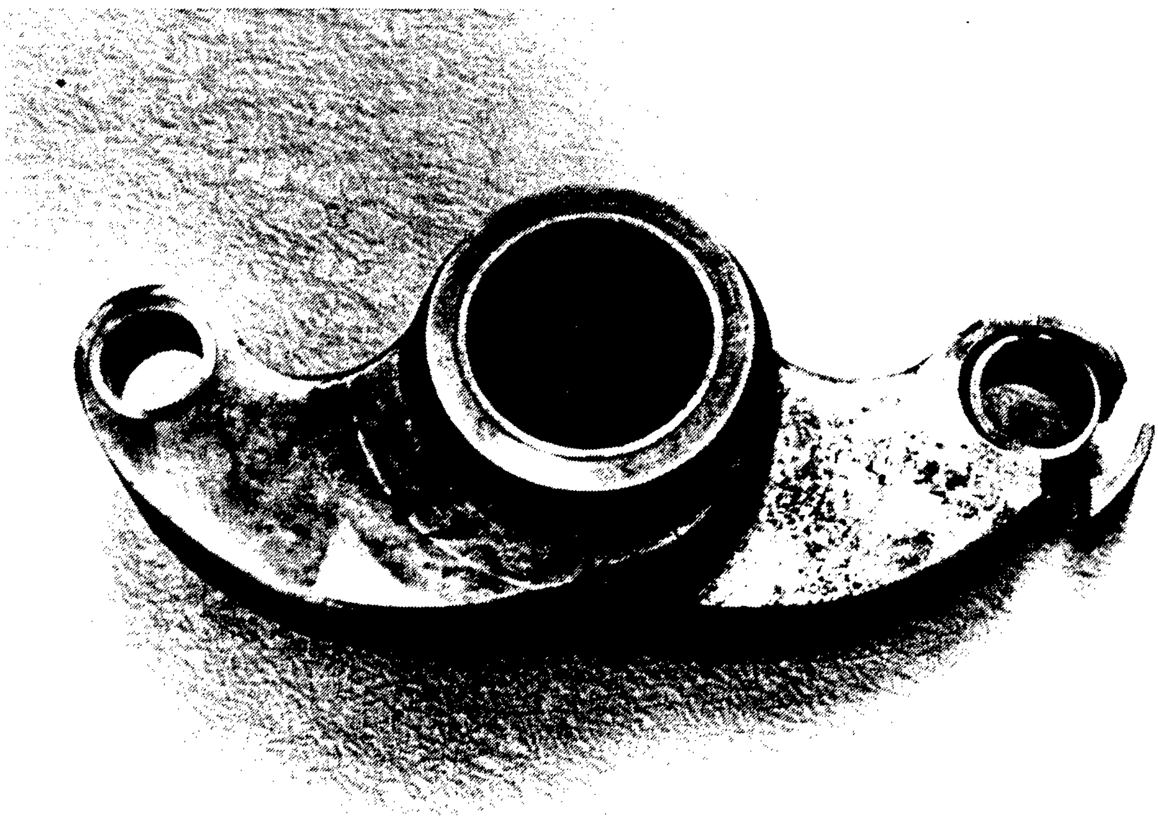


Figure 5-10. Cast Iron Rocker Arm Failure (B/N-03)

5.5.4. Engine Build B/N-04. A new set of rockers were made from LaSalle stressproof steel (Figure 5-11). New connecting rods were obtained by modifying commercial rods for a 35 HP Volkswagen engine, and welding on a double clevis as shown in Figure 5-12.

Evaluation of the engine with the new manufactured rockers and connecting rods showed an increase in the friction horsepower measured (Figure 5-13) compared to the results obtained on B/N-03. This was attributed to increased inertia of the steel components. Additionally, a new fuel pump set to run at engine speed was installed on this build. The previous pump system, built at UCD, was set up for half engine speed.

Further engine operation on April 27, 1984 resulted in an emergency shutdown caused by a major failure of the pistons and water cooled cylinder. The extent of the damage precluded complete failure analysis. Probable cause appeared to be a fatigue failure of the cylinder near the rocker clearance slots causing the piston ring to catch, resulting in the intake piston jamming.

A rebuild of the metal engine was initiated, including the crankshaft and rework of the crankcase. A new steel cylinder without water cooling was made to the ceramic design specifications, thus allowing interchangeability of hardware within the engine bed. New aluminum pistons sized for the steel cylinder were also remanufactured in the Eaton machine shop.

Table 5-6. Engine Build B/N-04 and Results

Components	Identification	Remarks
Cast Iron Cylinder	-	No change from B/N-02 and 03.
Aluminum Pistons, Cast Iron Piston Rings	-	No change from B/N-03.
New Rockers and Connecting Rods	-	Rockers made at Eaton, connecting rods modified VW engine rods.
<u>Operating Results</u>		<u>Remarks</u>
Engine Evaluation		Friction horsepower increased for engine assembly compared to B/N-03 measurement.

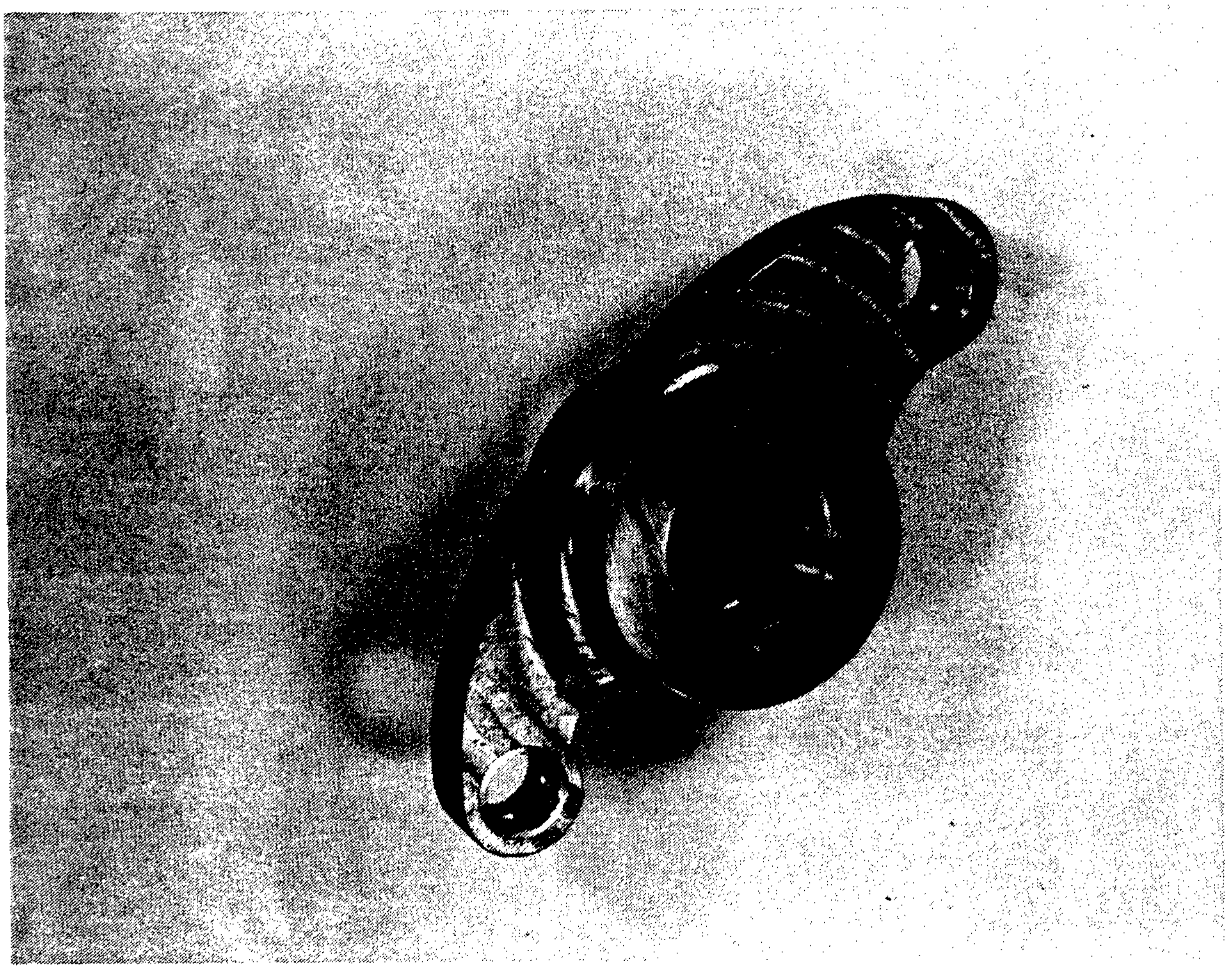


Figure 5-11. Steel Rocker Arm (B/N-04)

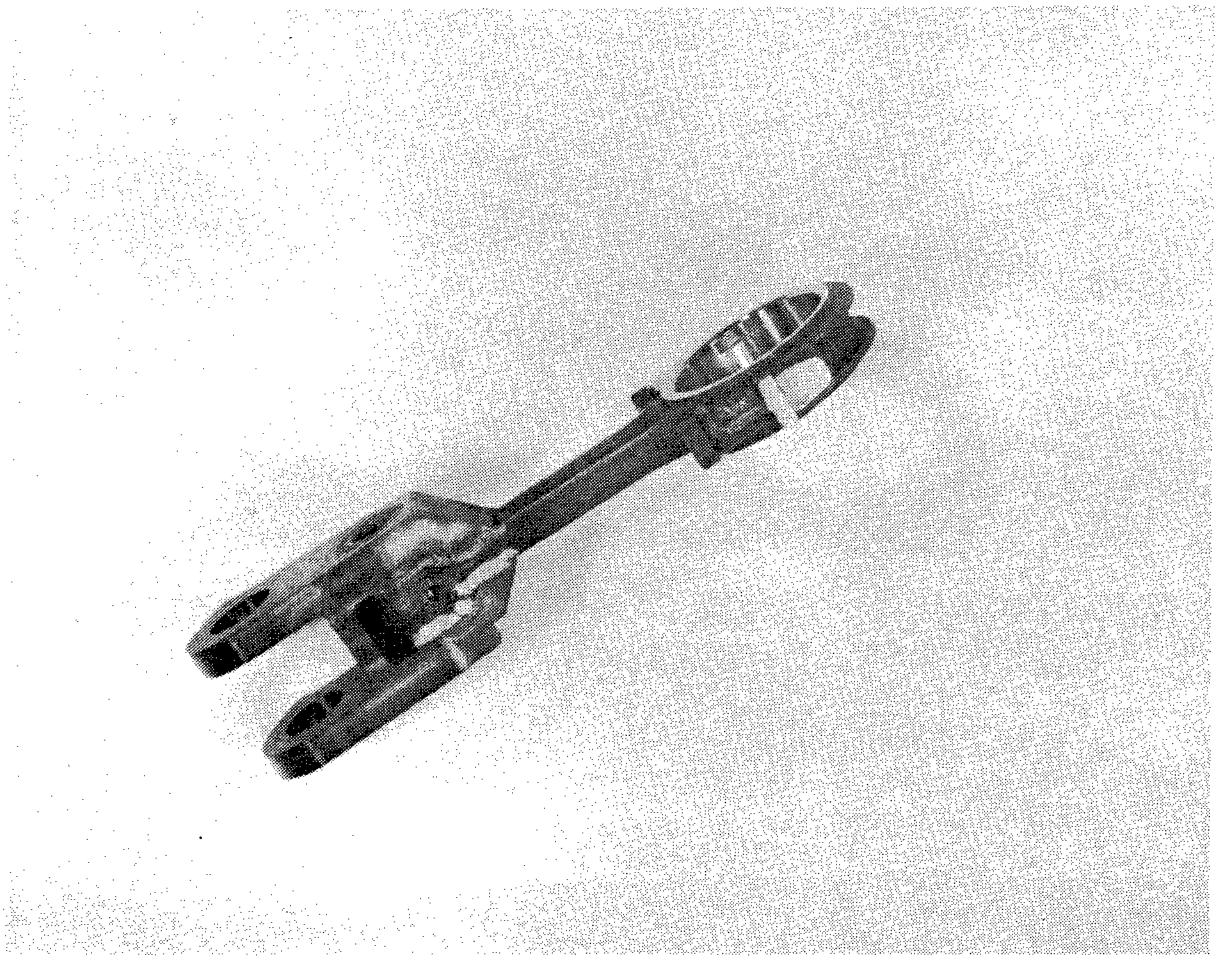


Figure 5-12. Double Clevis Steel Connecting Rod (B/N-04)

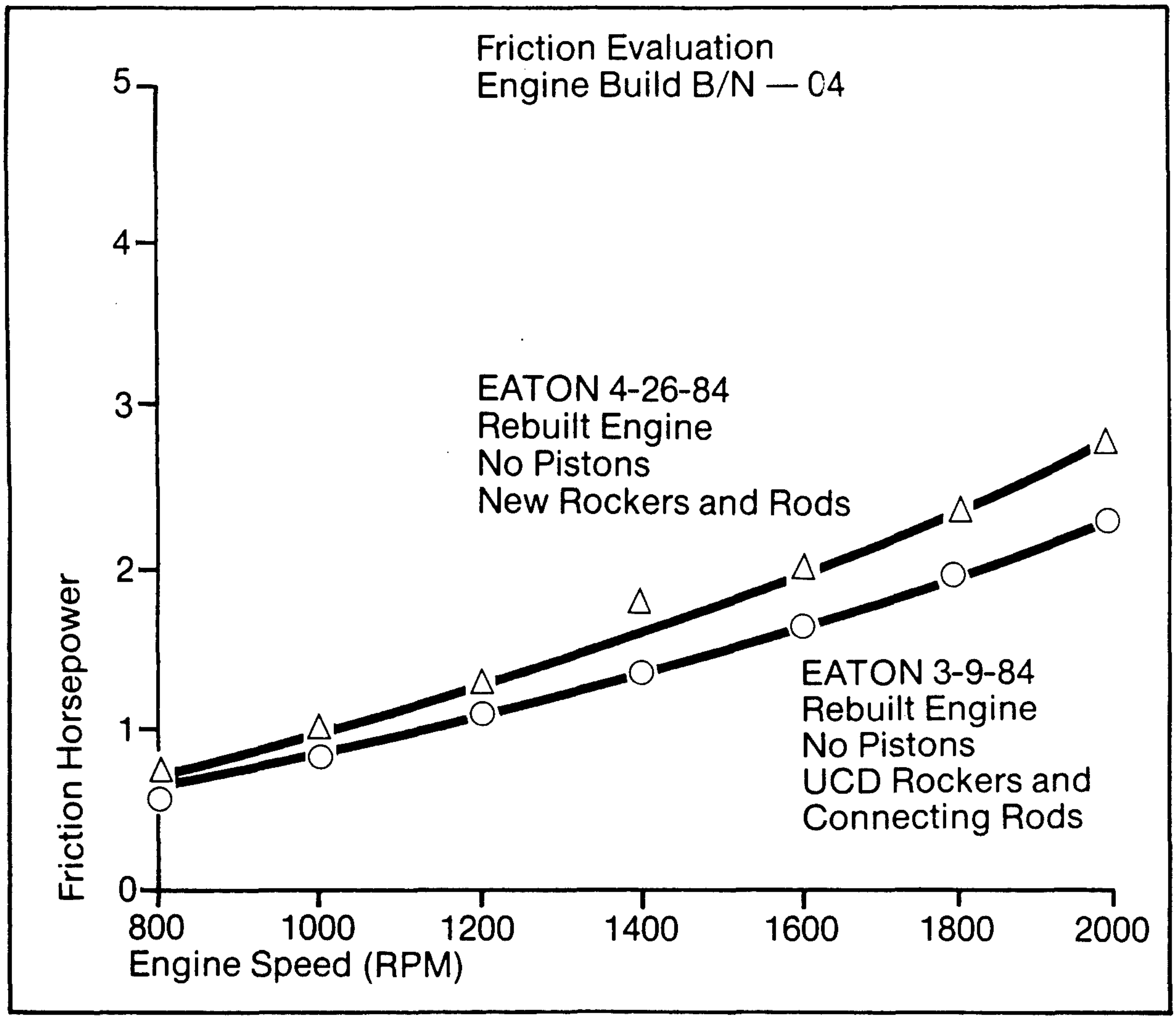


Figure 5-13. Bare Engine Friction Comparison for Rocker Arm Modifications

Table 5-6. Engine Build B/N-04 and Results (Continued...)

Components	Identification	Remarks
Continued Engine Testing -		
April 27, 1984		
- Engine Firing - 2.5 Hrs. - Emergency stop during test		Major failure of watercooled cylinder, and aluminum pistons.
Component Weight Measurement -	Connecting Rods	Rocker Arms
Original Timoney	2.16 lbs.	6.60 lbs.
Eaton Manufactured	2.35 lbs.	8.65 lbs.
Build Date: April 25, 1985		

5.5.5. Engine Build B/N-05. A new engine build was initiated with sintered alpha silicon carbide components. The redesigned cylinder assembly shown in Figure 5-14, is composed of an SASC cylinder with 4 exhaust and 4 inlet ports either side of two injector holes 180° apart. A floating (0.001-0.002 inches O.D. clearance) stiffening ring covers the central 2 inches of the cylinder. The ring provides additional hoop strengthening for the combustion zone and serves to hold the injector nozzle. Roundness traces were obtained for the inside diameter of the cylinder and stiffening ring, and the outside diameter of the pistons. SASC component design details and profile measurements are presented in Appendix C. The final engine assembly is shown in Figure 5-15 and 5-16.

Preliminary engine evaluation was initiated on July 20, 1984. Motoring evaluation at 500-800 rpm resulted in an intermittent "chirping" noise which gradually disappeared after several hours of running. Inspection of the cylinder through the ports revealed some abrasion on the bore. Inspection of the pistons after disassembly showed slight piston abrasion resulting from apparent assembly interference, and wear debris on the skirt which could be easily rubbed off (Figure 5-17).

Further motoring and brief firing trials were conducted following engine reassembly. During these additional tests a clicking noise occurred that was traced to reversals in the piston carrier assembly. Also, the engine developed a vibration problem that was not present during previous tests. Further testing was terminated and modification to the metal carrier was initiated.

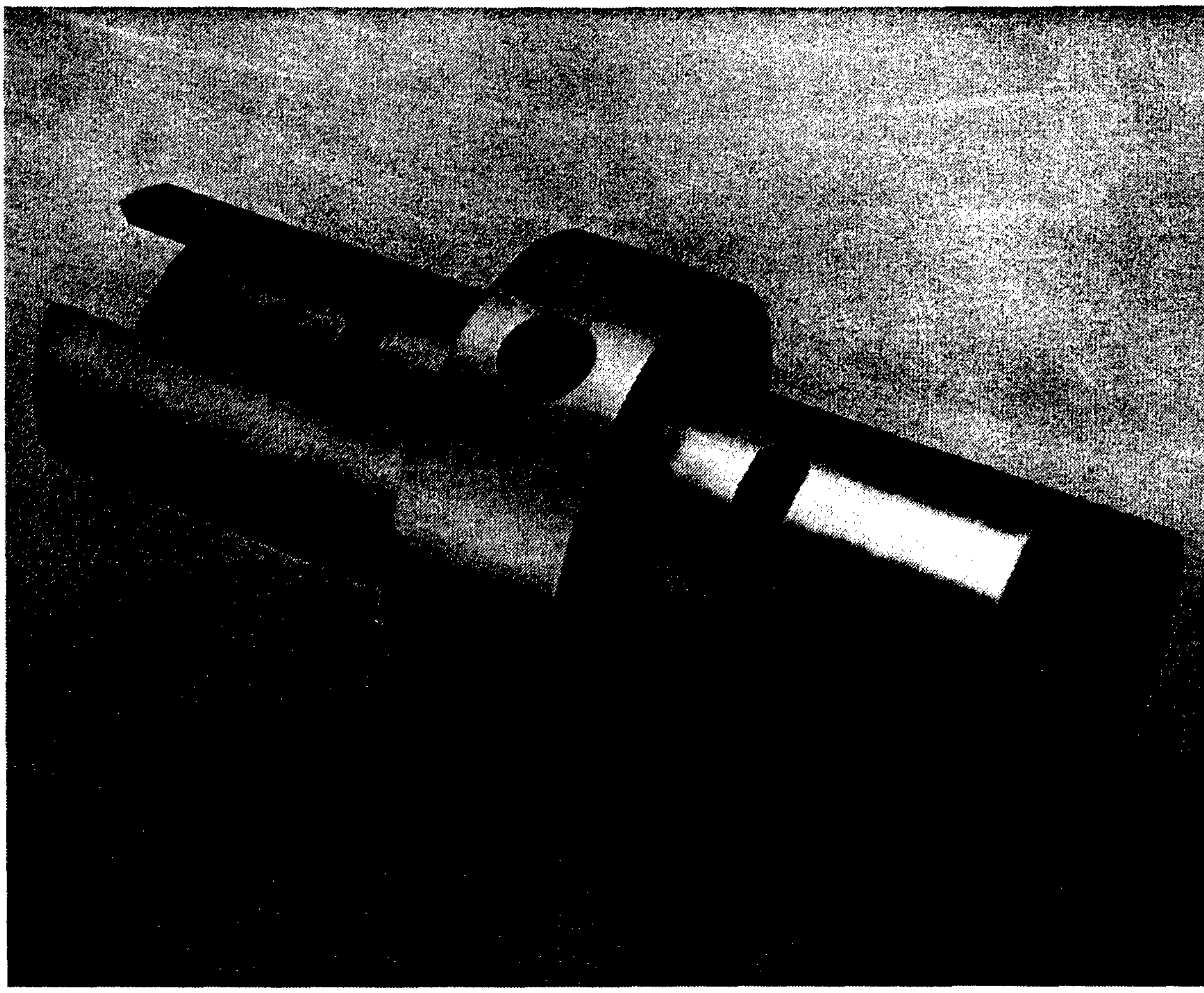


Figure 5-14. Redesigned SASC Cylinder with Stiffening Ring

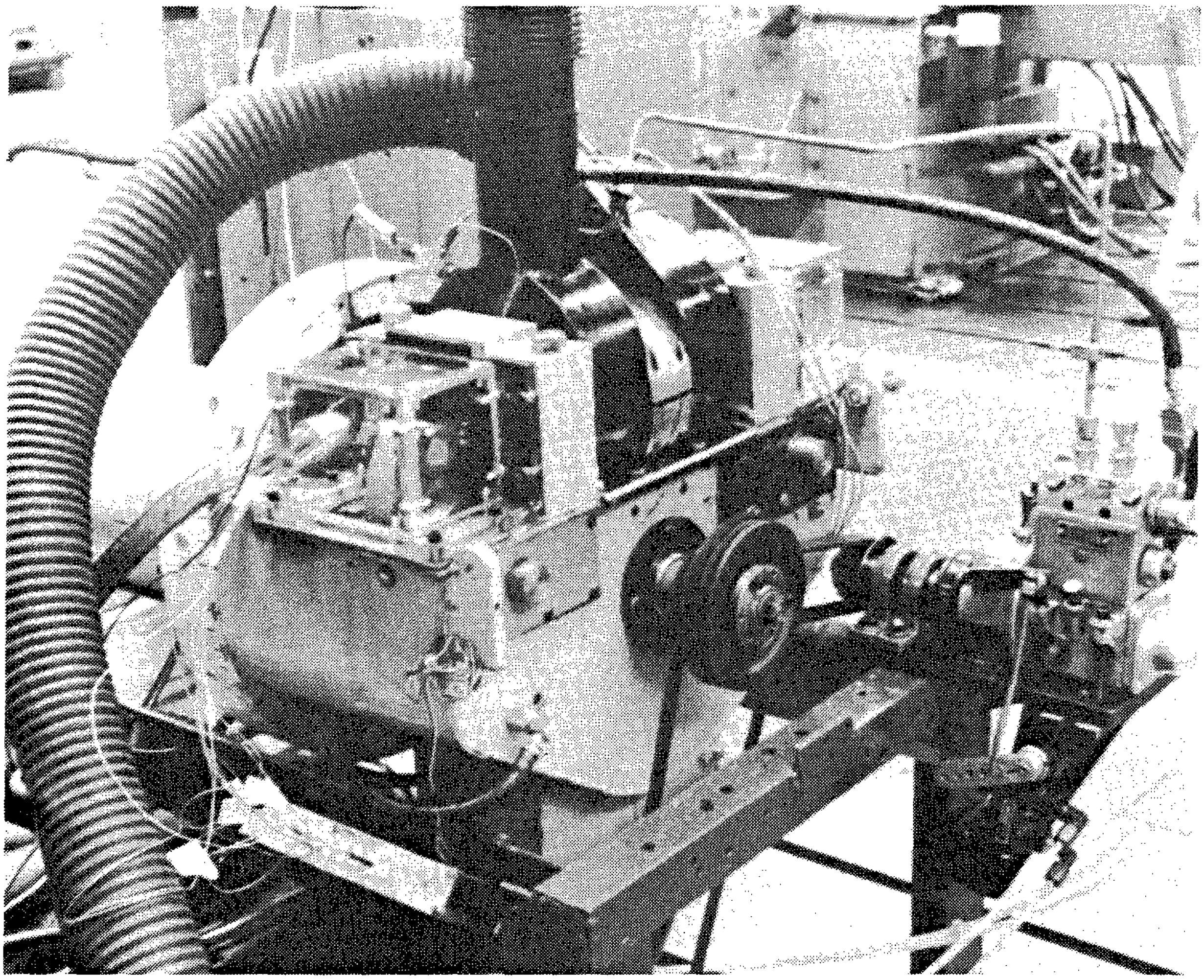


Figure 5-15. Overall View of Engine for Ceramic Component Testing

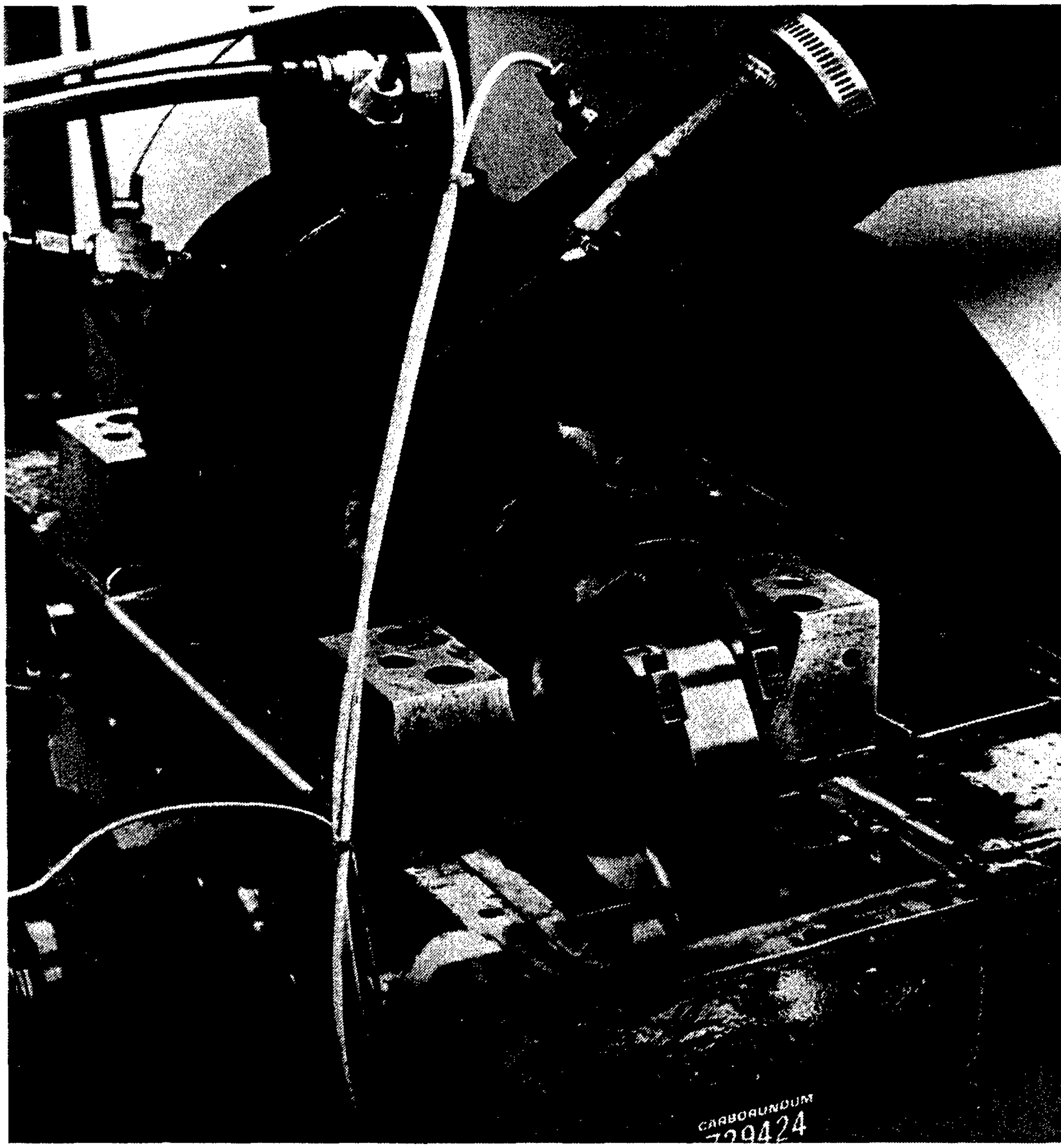


Figure 5-16. Closeup View of Engine with Redesigned SASC Cylinder

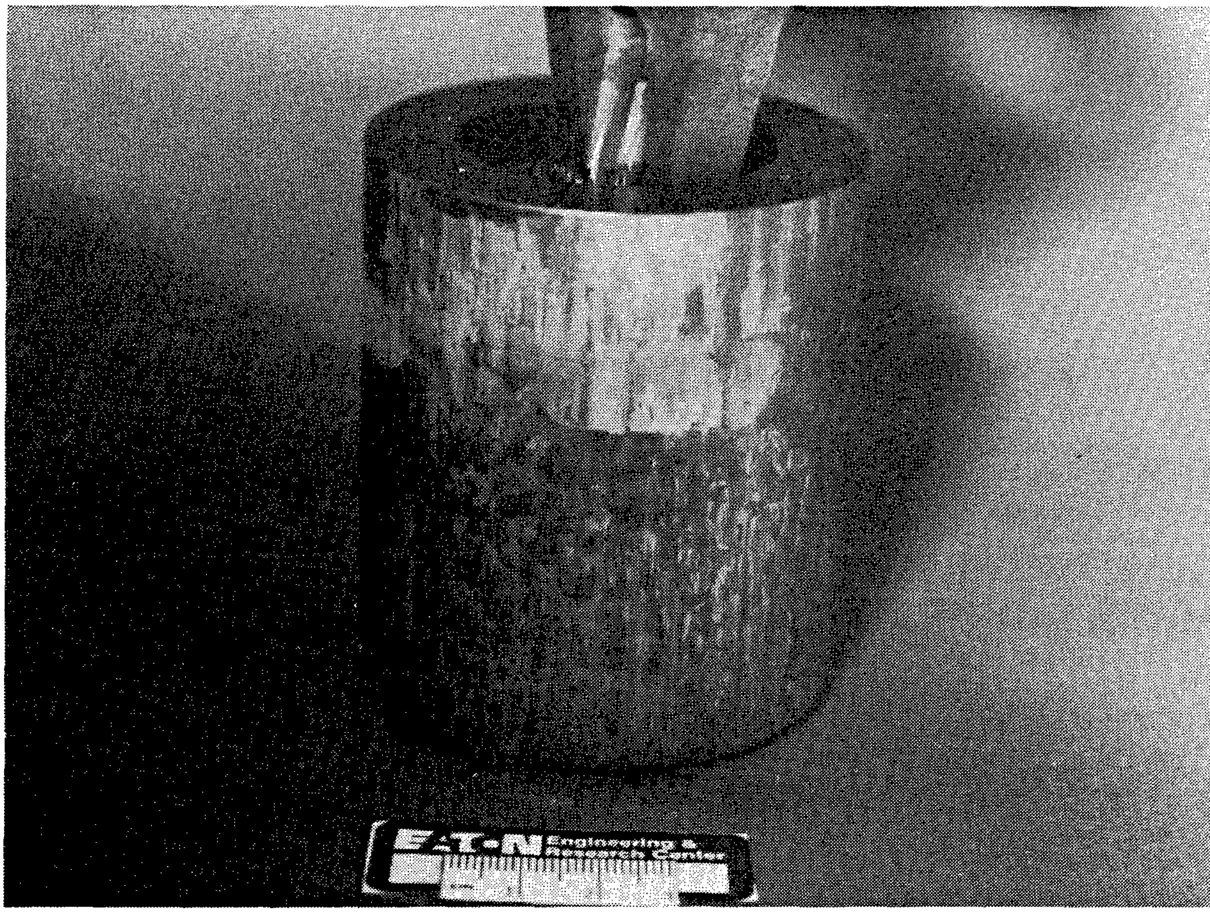


Figure 5-17. SASC Piston After Motoring (B/N-05)

Disassembly of the piston/carrier revealed the ceramic mullite spacers had cracked, increasing the clearance between the carrier and the retainer ring. A design modification to the piston carrier was made incorporating Allen-type set screws to take up any clearance between the spacer and the carrier after assembly, as shown in Figure 5-18.

As recommended by Ricardo Consulting Engineers, the ceramic mullite spacer was replaced with a steel spacer between the carrier and the underside of the piston crown. Results from the thermal analysis study showed undercrown insulation creates a severe thermal stress gradient, and should be avoided.

The reassembled SASC engine with the modified carrier was demonstrated for TACOM personnel on August 29, 1984. The cylinder assembly and stiffening ring were instrumented with thermocouples as shown in Figure 5-19. Temperature measurements showed the stiffening ring heated up uniformly with the cylinder. During this evaluation run the vibration problem became more pronounced with critical displacements occurring at 600 rpm and 1250 rpm. A total of approximately 48 hours running time was accumulated.

Avoiding sustained engine operation at the critical frequencies, friction measurements were obtained on the SASC components. The friction horsepower results show a 5-8% increase over the metal engine from build B/N-03. This increased friction result was contrary to the previous reduced friction results with SASC components, and is likely explained by the piston to cylinder interference noted during the preliminary evaluation.

After 73 hours of total motoring with the SASC hardware, engine firing was attempted over a period of 1.5 hours before terminating testing due to extremely poor combustion. Inspection after engine teardown revealed the cylinder had cracked at mid-length.

Analysis of the fracture surfaces revealed a bending failure of the cylinder shown in Figure 5-20. Abraded areas of the pistons and matching areas on the cylinder bore are shown in closeup views Figure 5-21 and 5-22. It was concluded that the stiffening ring, weighing 8 lbs., imposed a substantial cyclic bending load on the cylinder, caused by the engine vibration and rocking couple from the crankshaft. Additionally, misalignment of the piston axis and cylinder axis, as apparently evidenced by component abrasion, may have contributed further to the bending stresses.

Given the tight design clearances, it was decided the risk of piston-to-cylinder misalignment and resulting interference was too high with a wrist pin carrier/connecting rod attachment. Therefore, it was decided subsequent ceramic piston assemblies would incorporate the original ball and socket design to allow freedom of alignment. Secondly, the crankcase required further structural strengthening to reduce the lateral displacement due to the vibration problems. Thirdly, the cylinder assembly should be allowed to float in the support trunnions to avoid transmitting bending forces to the cylinder. Additionally, the cylinder and stiffening ring should be assembled with a line-to-line shrink fit to eliminate any movement of the ring on the cylinder.

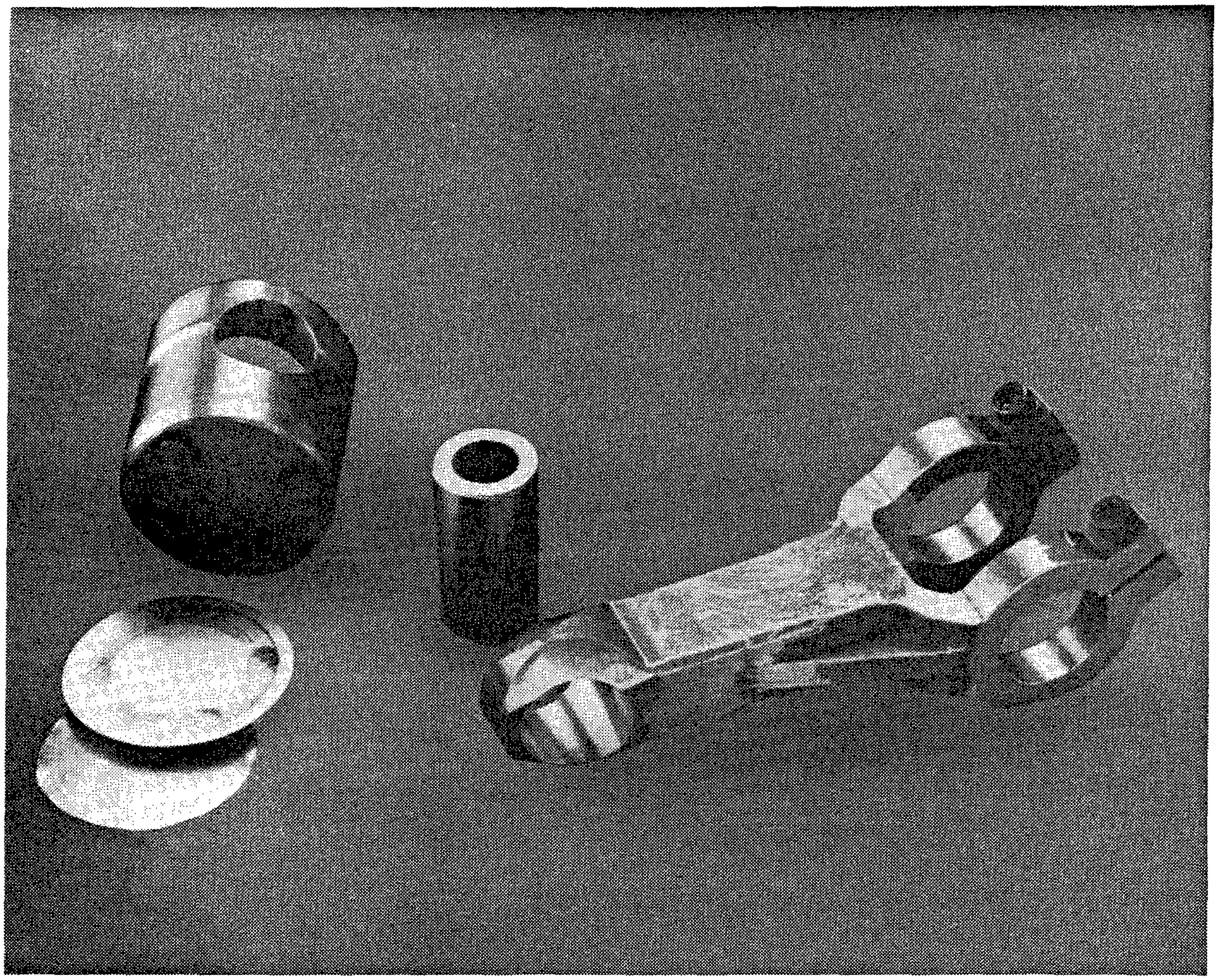


Figure 5-18. Modified Piston Carrier Assembly

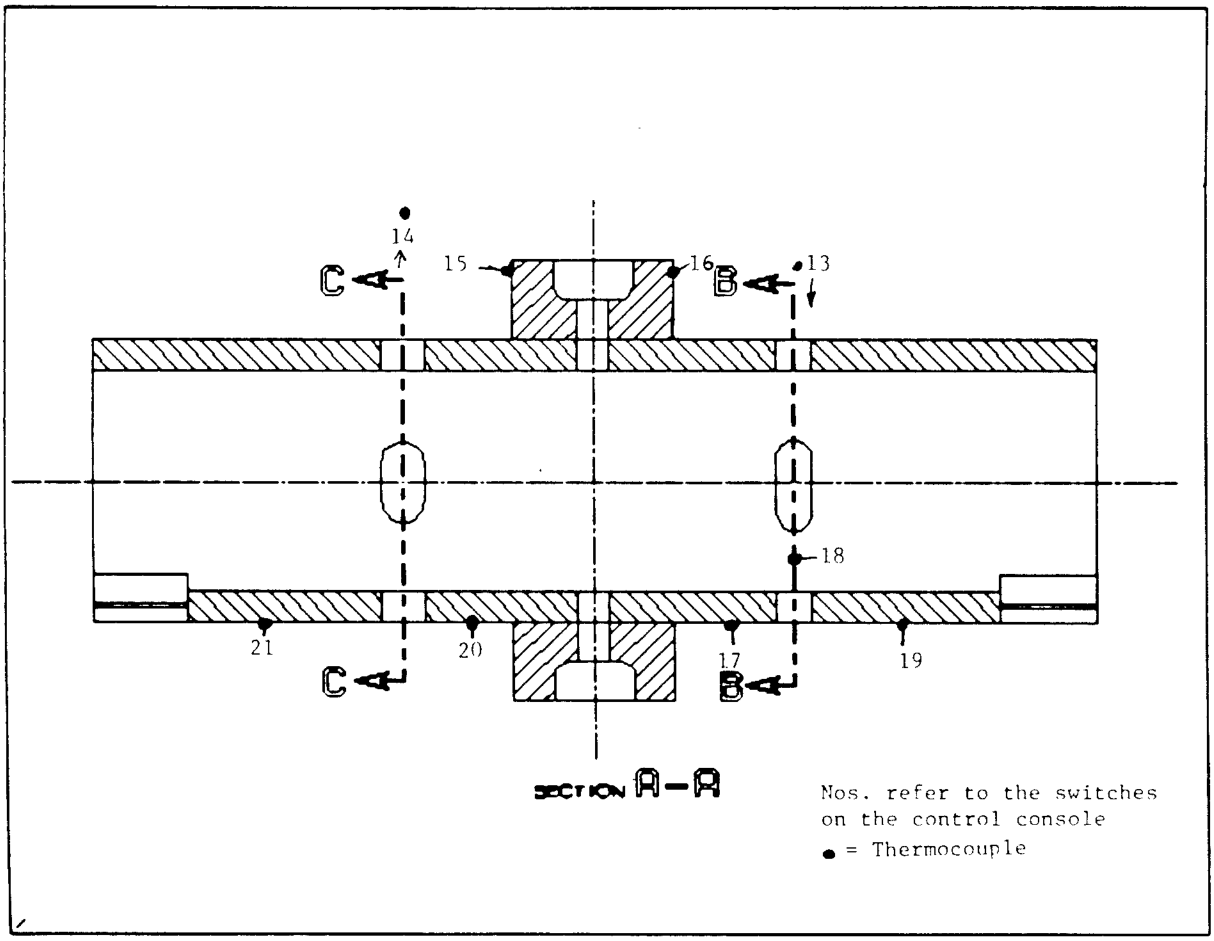


Figure 5-19. Cylinder Schematic with Thermocouple Locations

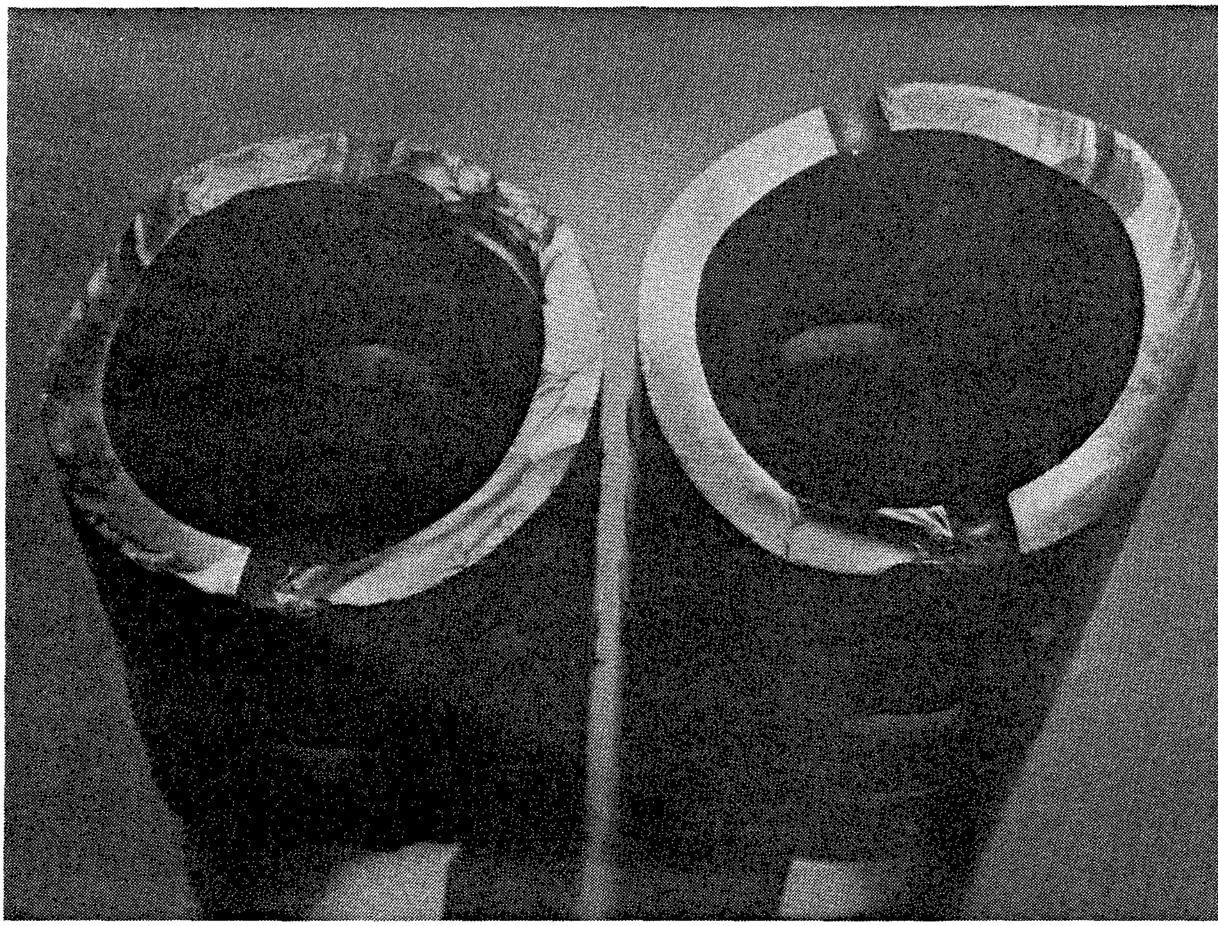


Figure 5-20. SASC Cylinder - Bending Failure (B/N-05)

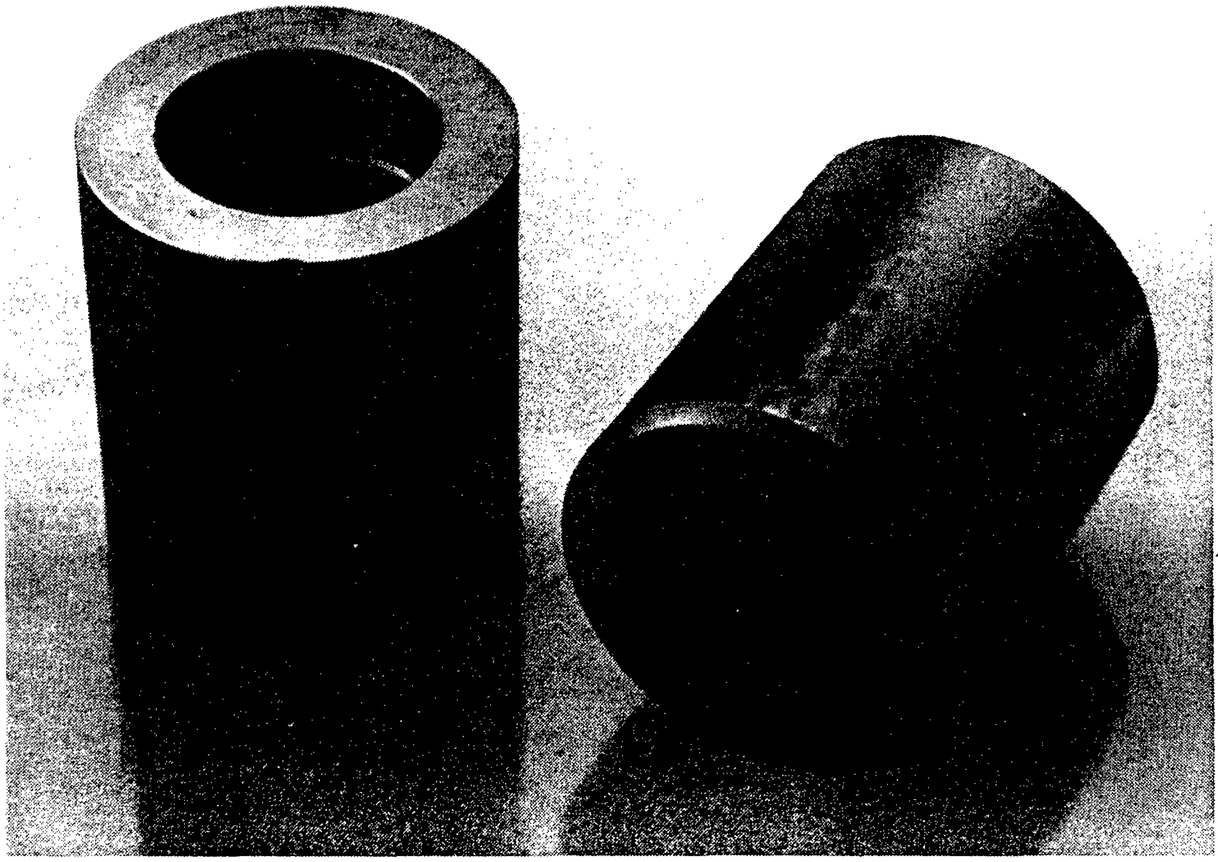


Figure 5-21. SASC Piston Surface Abrasion (B/N-05)

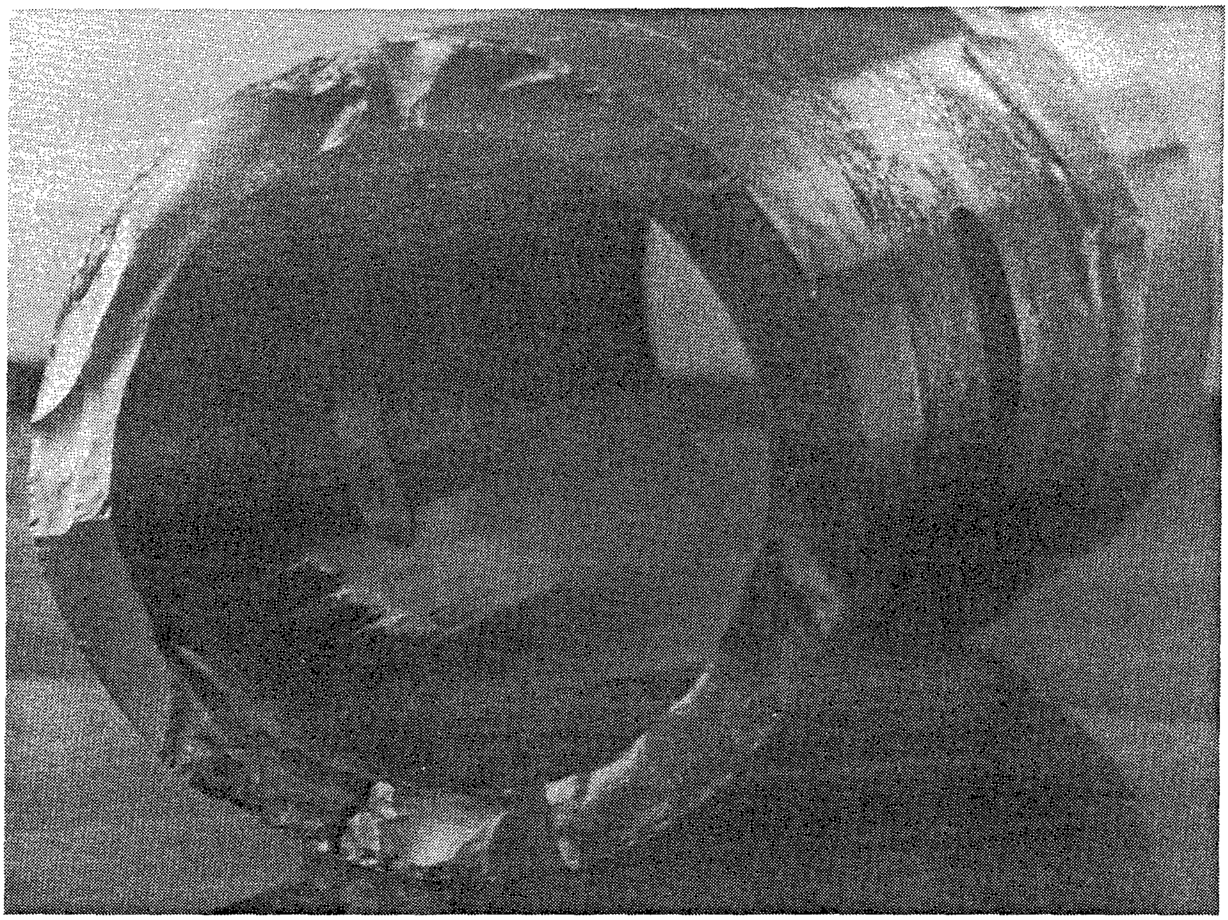


Figure 5-22. SASC Cylinder Bore Abrasion (B/N-05)

Table 5-7. Engine Build B/N-05 and Results

Components	Identification	Remarks
SASC Cylinder and SASC Stiffening Ring	C/N-01	Modified cylinder design and floating stiffening ring with .001-.002 inches clearance.
SASC Pistons with Metal Carrier	P/N-6 and 7	Revision #1 - Carpenter 42 Steel carrier and a mullite ceramic spacer. Revision #2 - Allen-type adjusting screws added and steel spacer.
<u>Operating Results</u>		<u>Remarks</u>
Preliminary Operation:		
Engine Motoring - 5 Hrs.		Chirping noise detected; piston and cylinder bore wear distress marks observed.
Engine Motoring - 8 Hrs. Engine Firing - .2 Hrs.		Clicking noise noted, varied with engine speed, testing terminated.
Engine Evaluation Resumed:		
Engine Motoring - 34.75 Hrs. (maximum engine speed 1600 rpm)		Piston carrier modified-Revision #2, measured compression ratio of 18-19.8:1, cylinder/ring assembly temperature profiles measured. Vibration problems at 600 rpm and 1,250 rpm.
Engine Evaluation (full ceramic assembly)		Friction horsepower increased 5-8% over results for B/N-03 with aluminum pistons.

Table 5-7. Engine Build B/N-05 and Results (Continued...)

Components	Identification	Remarks
Engine Motoring - 38.25 Hrs. Engine Firing - 1.5 Hrs.		
		Erratic firing, poor combustion and blowby, testing terminated after 1.5 hrs. Inspection revealed cylinder cracked at mid section; one cylinder half shifted. (September 7, 1984)
Cumulative Operation Time -	Motoring/Firing	Firing Hrs.
SASC Cylinder Liner/Ring Assembly and SASC Pistons	87.7	1.7
Build Date: July 20, 1984		

5.5.6. Engine Build B/N-06. The engine vibration problem was eventually traced to an out-of-balance in the coupling between the dynamometer and the engine and corrected. The unbalance problem apparently developed due to the abrupt stops from the previous engine failures.

Friction horsepower measurements were obtained for the engine without connecting rods and pistons attached. Figure 5-23 illustrates a reduction in friction for the bare engine compared to the previous B/N-03 metal engine build. The improved friction performance is directly attributed to the extensive reconditioning of metal components following the engine failure of B/N-04.

A steel cylinder without a cooling jacket was fabricated and baseline friction horsepower measurements obtained on the lubricated metal engine. The friction horsepower curve can be seen to be essentially the same as the complete metal engine from build B/N-03 with a water-cooled cast iron cylinder. Friction results are also tabulated in Table 5-8 for the metal assembly (steel cylinder, aluminum pistons).

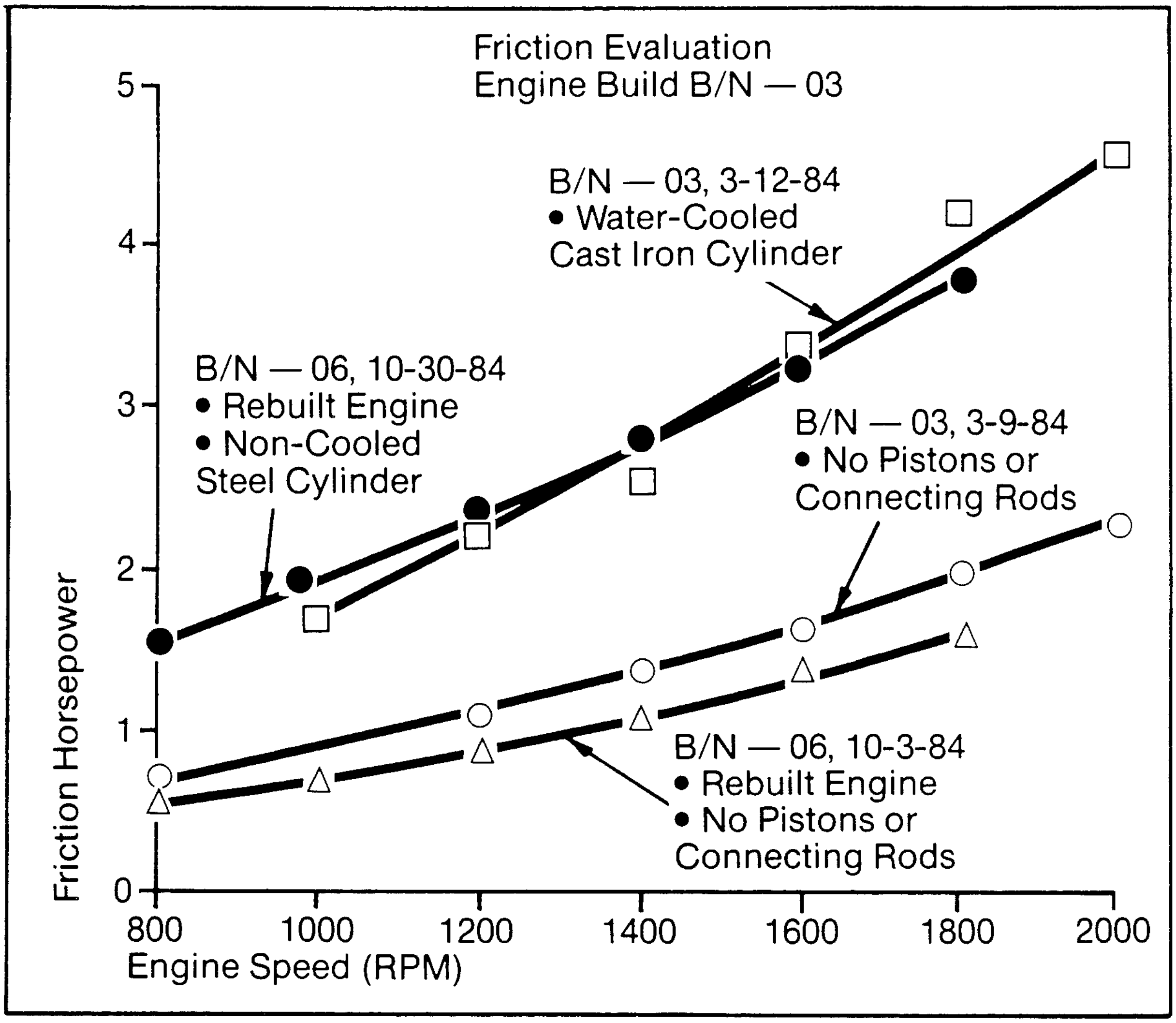


Figure 5-23. Engine Friction Comparison Between Build B/N-03 and Build B/N-06

Friction measurements for this engine build (B/N-06) provide the baseline comparison for all subsequent ceramic engine friction evaluations.

Table 5-8. Baseline Friction Horsepower Engine Build B/N-06

Engine Speed (RPM)	Torque (Ft.-lbs.)*	FHP*	Torque (Ft.-lbs.)+	FHP+
800	3.8	0.58	9.9/10.1	1.5/1.54
1000	4.2	0.70	10.1/10.5	1.92/2.0
1200	4.5	0.91	9.8/10.0	2.24/2.3
1400	5.0	1.1	10.3/10.6	2.75/2.83
1600	5.35	1.4	10.8/11.0	3.3/3.35
1800	5.7	1.6	11.4/11.6	3.91/3.98

* Engine without pistons and connecting rods
\+ Full engine assembly with non-cooled steel cylinder

Table 5-9. Engine Build B/N-06 and Results

Components	Identification	Remarks
Steel Cylinder	--	Eaton manufactured, duplicate design of SASC C/N-01, no cooling provided.
Aluminum Pistons with new rings	--	Eaton manufactured, pistons (piston design detail - reference Appendix D), commercial Briggs and Stratton cast iron rings.
<u>Operating Results</u>		
Engine Evaluation Accumulated Time: Engine Motoring - 15 Hrs. Engine Firing - .25 Hrs.		Baseline metal engine friction test, compression ratio set for 18:1.
Build Date: October 8, 1984		

5.5.7. Engine Build B/N-07. A new engine build was initiated with sintered alpha silicon carbide components. Room temperature dimensional parameters were obtained for the pistons and cylinder (Table 5-10). Profile measurement details are presented in Appendix E.

Table 5-10. Dimensional Parameters for Piston/Cylinder Build B/N-07

Parameter	Values
Diametral Clearance (Nominal), microinches	300 - 500
Cylinder I.D. Runout (Maximum), microinches	50
Piston O.D. Runout (Maximum), microinches	100

Preliminary engine evaluation was initiated on January 10, 1985. Motoring at 800-1,300 rpm resulted in smooth operation without vibration. Disassembly and inspection after 1.75 hours operation showed the cylinder and pistons in good condition. The pistons were reassembled and engine operation resumed. After 0.5 hours motoring at 500 rpm some debris was observed through the intake side end cover. Testing was terminated and inspection revealed a broken section at the cylinder intake end (Figure 5-24). No conclusion was drawn as to the failure cause based on analysis of the chip fracture surfaces due to material loss. Minor abrasive scoring resulted on the piston skirt (Figure 5-25). The components were judged to be in adequate condition for further testing after reworking the fractured surfaces by smoothing the sharp edges.

Motoring trials were resumed performing various operational checks. Engine operation appeared smooth over a speed range of 300 to 1,600 rpm. The engine was demonstrated for TACOM personnel January 30, 1985. Hot friction horsepower measurements (Table 5-11) were obtained for the full engine assembly as the engine was shutdown for inspection.

Table 5-11. Friction Horsepower for Build B/N-07

Engine Speed (RPM)	Torque (Ft.-lbs.)	FHP
800	6.9	1.05
1000	6.6	1.27
1200	7.2	1.65
1400	7.42	1.98

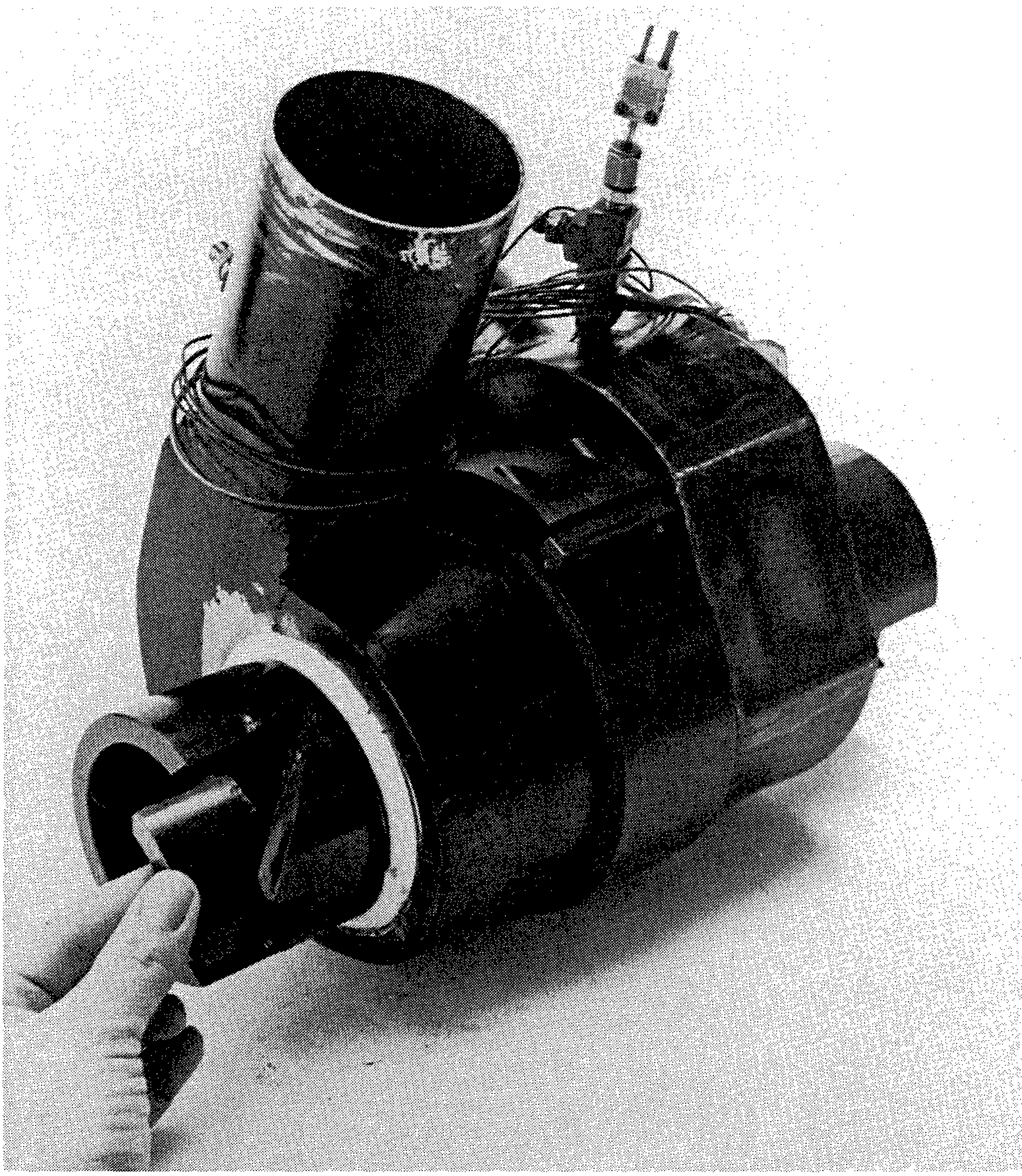


Figure 5-24. SASC Cylinder Damage (B/N-07)

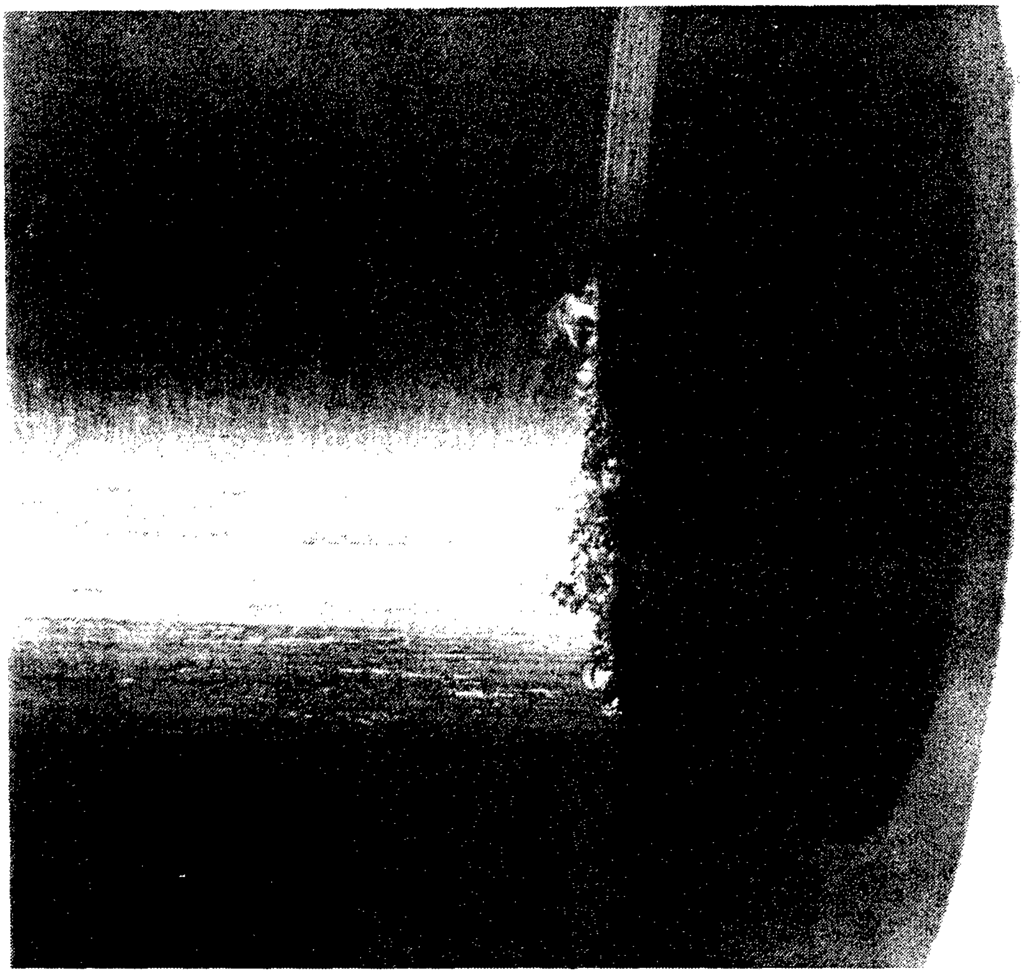


Figure 5-25. SASC Piston Abrasion (B/N-07)

Friction horsepower results shown in Figure 5-26 for the SASC ringless pistons show a 50 percent reduction in the contributed friction of the piston components compared to the baseline metal engine.

Inspection of the pistons and cylinder after firing revealed no further detrimental effects in addition to the components pre-test condition. The engine was allowed to cool down and testing resumed the following day. Initiation of firing resulted in erratic operation and poor combustion. After 1.5 hours of firing an audible crack was heard resulting in extensive fracturing to both the cylinder assembly and pistons before the dynamometer came to a complete stop.

A failure analysis was unable to be performed due to the extent of damage (Figure 5-27). Examination of the I.D. surface of several large cylinder fragments showed a high degree of surface polishing indicating rubbing contact between the cylinder and piston.

The consequence of the pre-existing broken cylinder end section probably lead to the failure. Observation of white smoke through the transparent end covers, prior to the catastrophic failure, suggests the likelihood that a crack propagated to the combustion zone, allowing exhaust leakage to the crankcase.

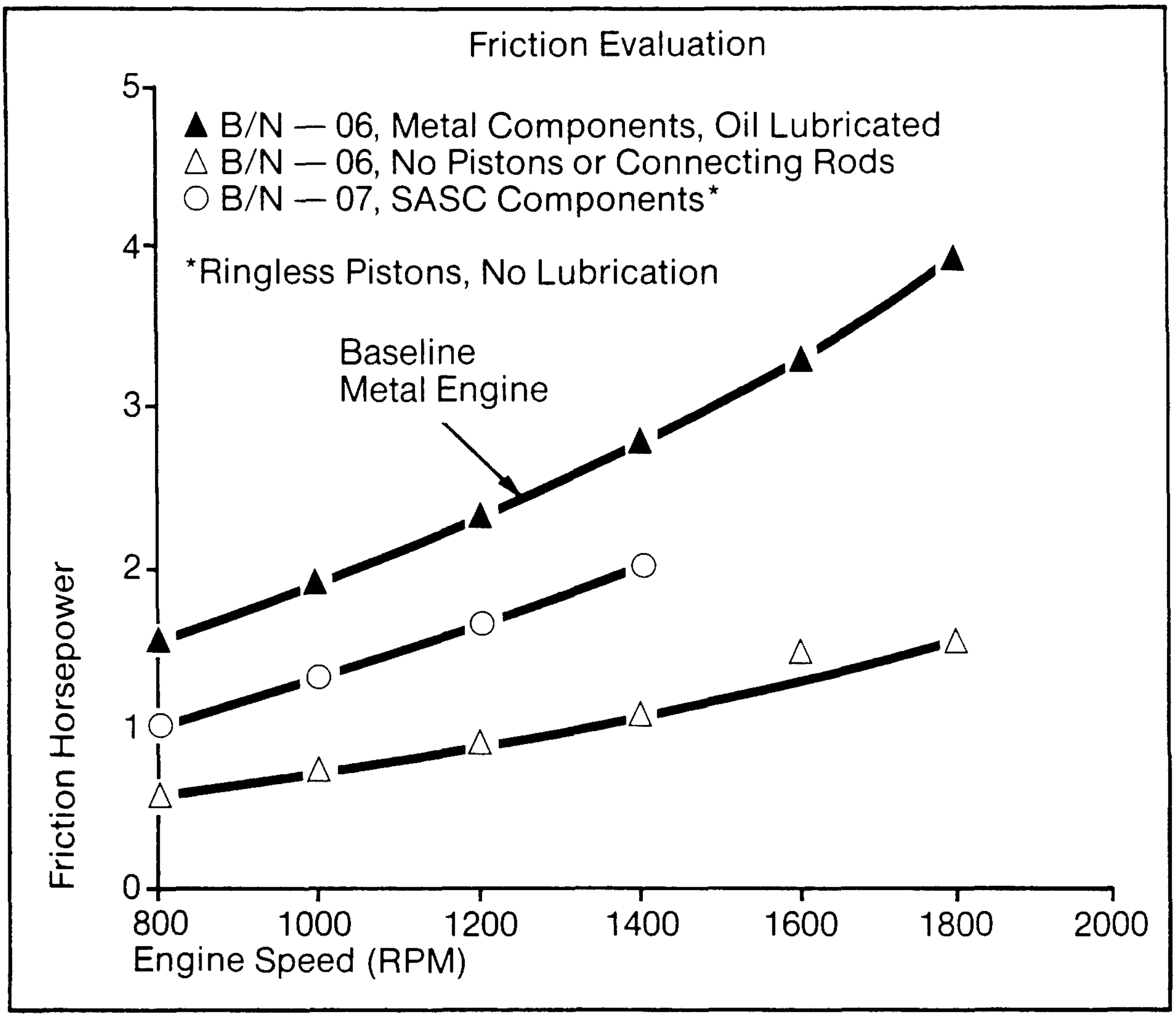


Figure 5-26. Engine Friction Comparison Between Metal Baseline B/N-06 and SASC Build B/N-07

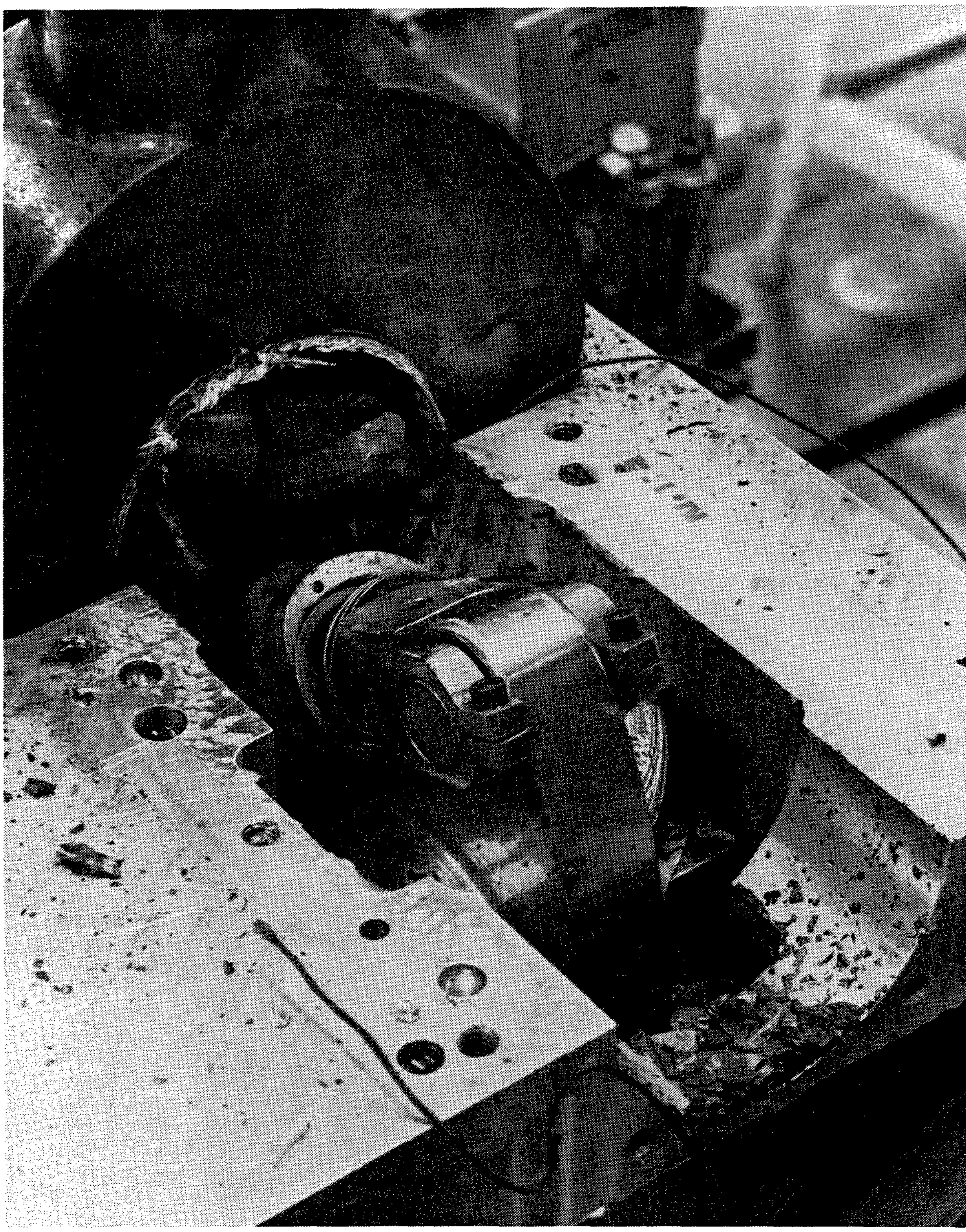


Figure 5-27. SASC Components Failure (B/N-07)

Table 5-12. Engine Build B/N-07 and Results

Components	Identification	Remarks
SASC Cylinder and SASC Stiffening Ring	C/N-02	Stiffening ring to linder .0001-.0002" interference fit.
SASC Pistons with Metal Carrier	P/N-2 and 5	Revision #3 - steel carrier ball and socket design modified for Allen-type adjusting screws.
Engine Bed		Floating cylinder design flat gaskets replaced by O-rings in trunnion support, crank case stiffening frame added.
<u>Operating Results</u>:		
Preliminary Operation: Engine Motoring - 2.25 Hrs.		Compression check 345 psi at 500 rpm, piston and cylinder inspection reveal cylinder fracture at skirt end and piston scoring - January 11, 1985.
Engine Evaluation: Engine Motoring - 21.1 Hrs. Engine Firing - 2.25 Hrs.		Operation to 1,600 rpm, engine accessory and timing adjustments, fuel limit control installed. Firing operation and friction testing initiated January 30, 1985.
Friction evaluation resumed: Engine Motoring - 1.5 Hrs. Engine Firing - 1.5 Hrs.		Firing erratic, 1.72 BHP at 1,200 rpm, poor combustion, fuel increased (2.4 BHP at 800 rpm), cylinder assembly and piston failure occurred - January 31, 1985.
Build Date: January 10, 1985		

5.5.8. Engine Build B/N-08. A new ceramic engine build was initiated with a backup sintered alpha silicon carbide cylinder and sialon pistons. Room temperature dimensional measurements were obtained for the pistons and cylinder shown in Table 5-13. Profile measurement details are given in Appendix F. The sialon pistons were class fit to the cylinder.

Table 5-13. Dimensional Parameters for Piston/Cylinder Build B/N-08

Parameter	Value
Diametral Clearance (Nominal), microinches	500 - 600
Cylinder I.D. Runout (Maximum), microinches	80
Piston O.D. Runout (Maximum), microinches	180

Preliminary engine evaluation was initiated on March 8, 1985. After 15 hours of motoring to 1,600 rpm, the engine was disassembled and component inspection revealed no evidence of wear on either the piston or cylinder bore.
Firing trials were initiated on March 12 and the engine demonstrated for TACOM personnel. Engine firing was smooth operating up to 2.14 BHP at 1,500 rpm. There was still some indication of vibration at 1,600 rpm. Hot friction horsepower measurements (Table 5-14) were made during engine shutdown after 2.5 hours of firing.

Table 5-14. Friction Horsepower for Build B/N-08

Engine Speed (RPM)	Torque (Ft.-lbs.)	FHP
800	7.26/6.85	1.90/1.04
1,000	8.2/6.98	1.56/1.32
1,200	8.0/8.3	1.82/1.89
1,300	8.3	2.05

Friction horsepower results for the ringless sialon pistons shown in Figure 5-28 exhibit a slight increase in friction over build B/N-07, but closely follow the SASC results of a 50% reduction in friction.

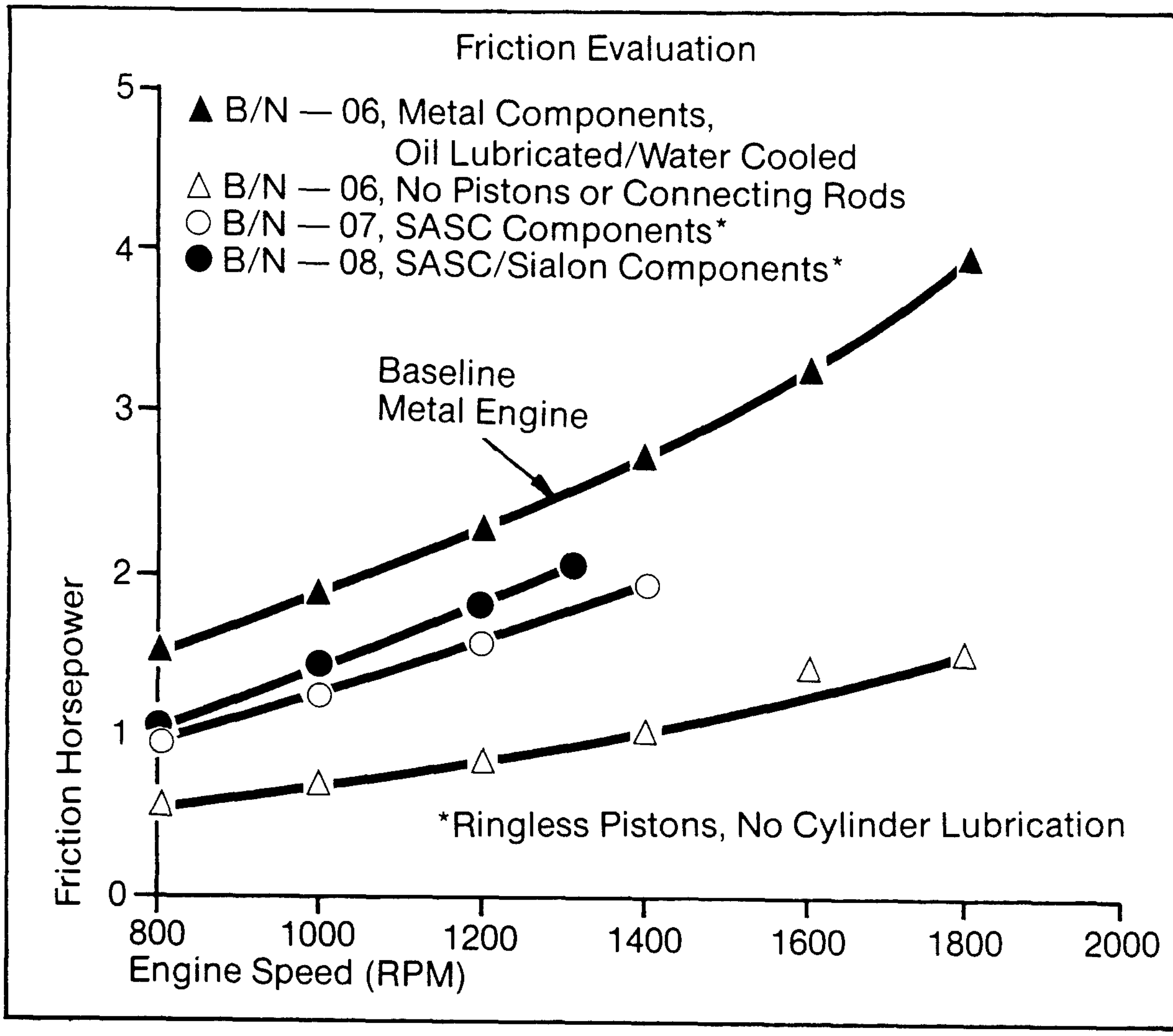


Figure 5-28. Engine Friction Comparison Between Metal Baseline B/N-06, SASC B/N-07 and Sialon/SASC B/N-08

Further evaluation was continued and periodic fuel consumption measurements made. At an engine speed of 1,125 rpm, the indicated specific fuel consumption (ISFC) ranged from 0.42 to 0.55 lb/HP-hr. However, lack of combustion chamber development and injection matching precluded specific fuel consumption being equivalent to developed engines. Exhaust gas temperatures were typically 430-475°F at 1,100 rpm and 1.5-2.0 BHP.

Testing was terminated after accumulating a total of 25.5 hours under firing conditions. The pistons were freely removed from the cylinder and inspection showed evidence of burnishing on the upper half of the sialon piston skirt as shown in Figure 5-29. The shiny circumferential ridges are burnished grinding marks which result from the surface pattern of the final O.D. grinding. Carbon deposits are evident on the piston crowns indicative of poor combustion, and also on the fuel injector tip shown in Figure 5-30.

Figure 5-31 shows the silicon carbide cylinder bore, with no indications of matching piston wear. Accumulated carbon deposits can be seen in the center of the cylinder combustion zone. The ceramic components showed no other physical evidence of distress and were judged to be in excellent condition.

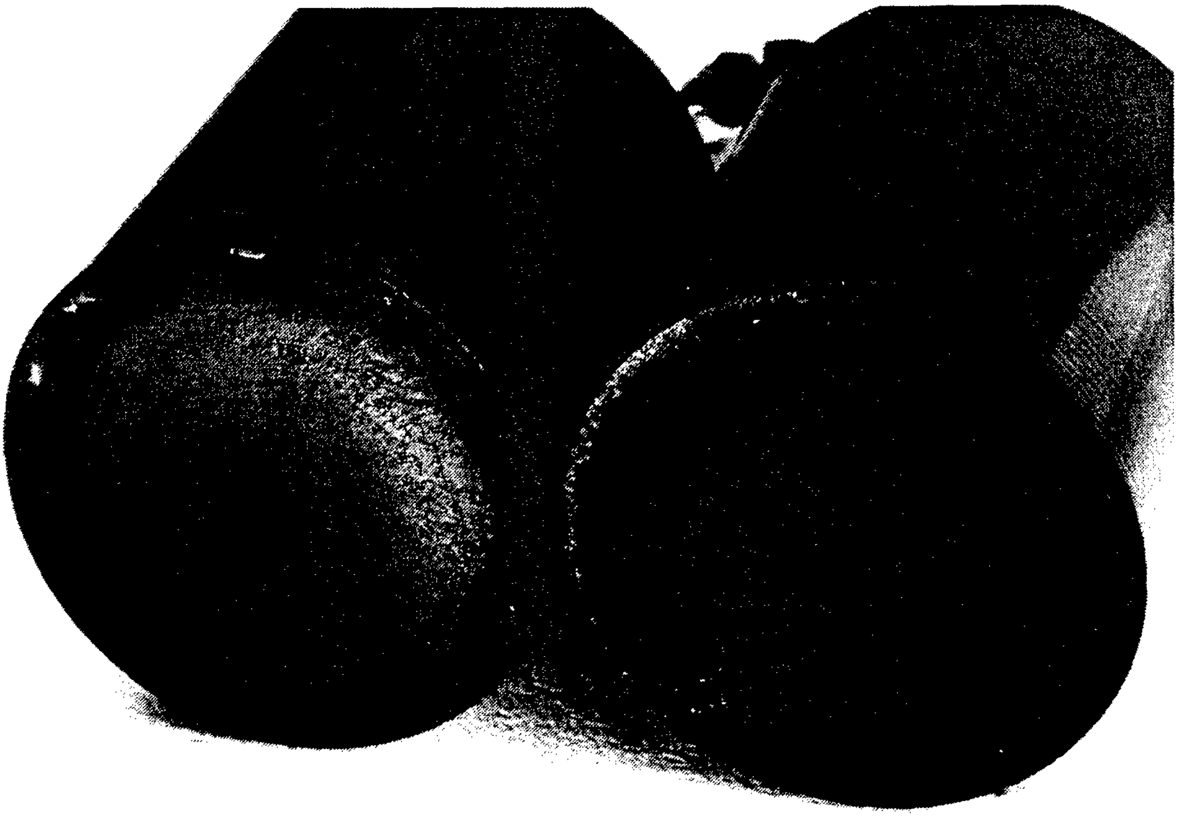


Figure 5-29. Sialon Pistons After Firing Tests (B/N-08)

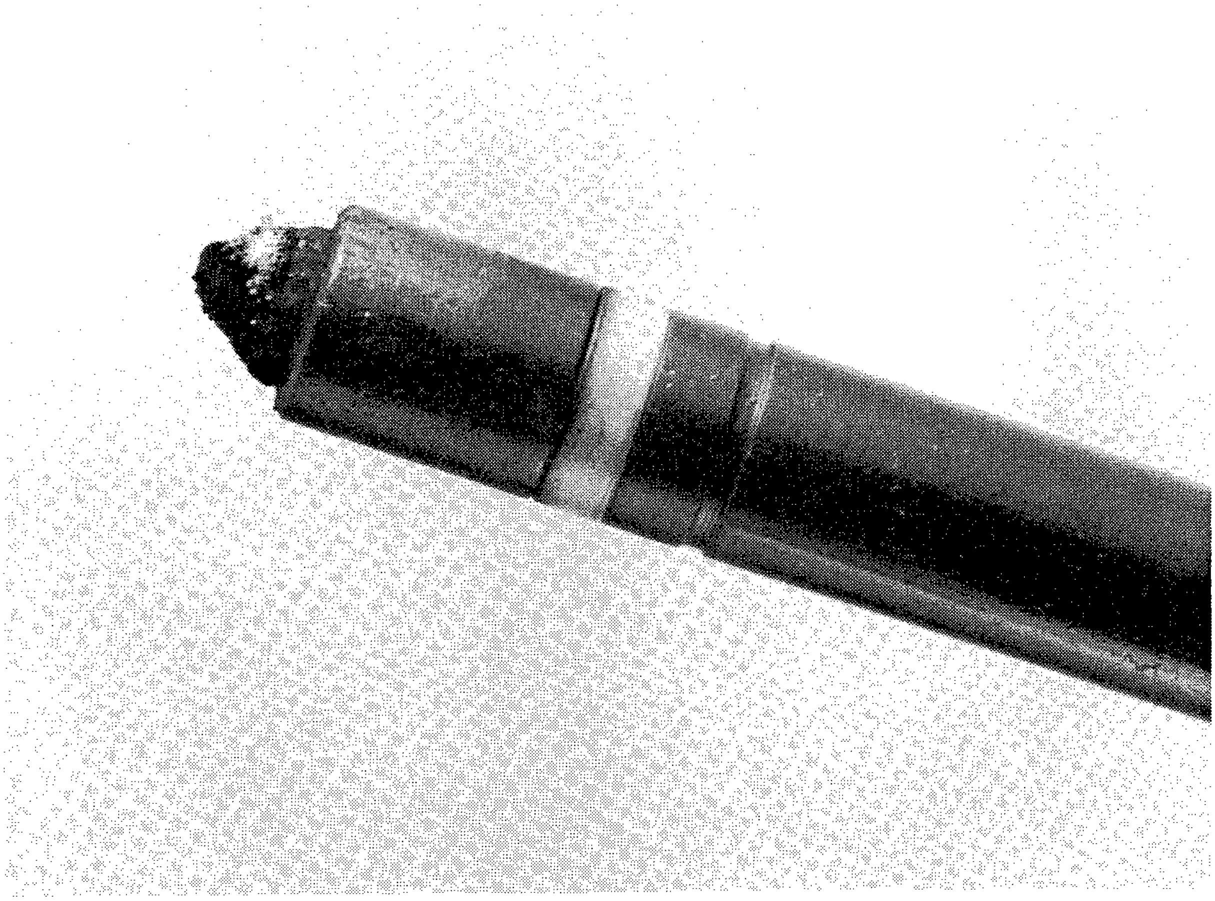


Figure 5-30. Injector Tip with Carbon Deposits

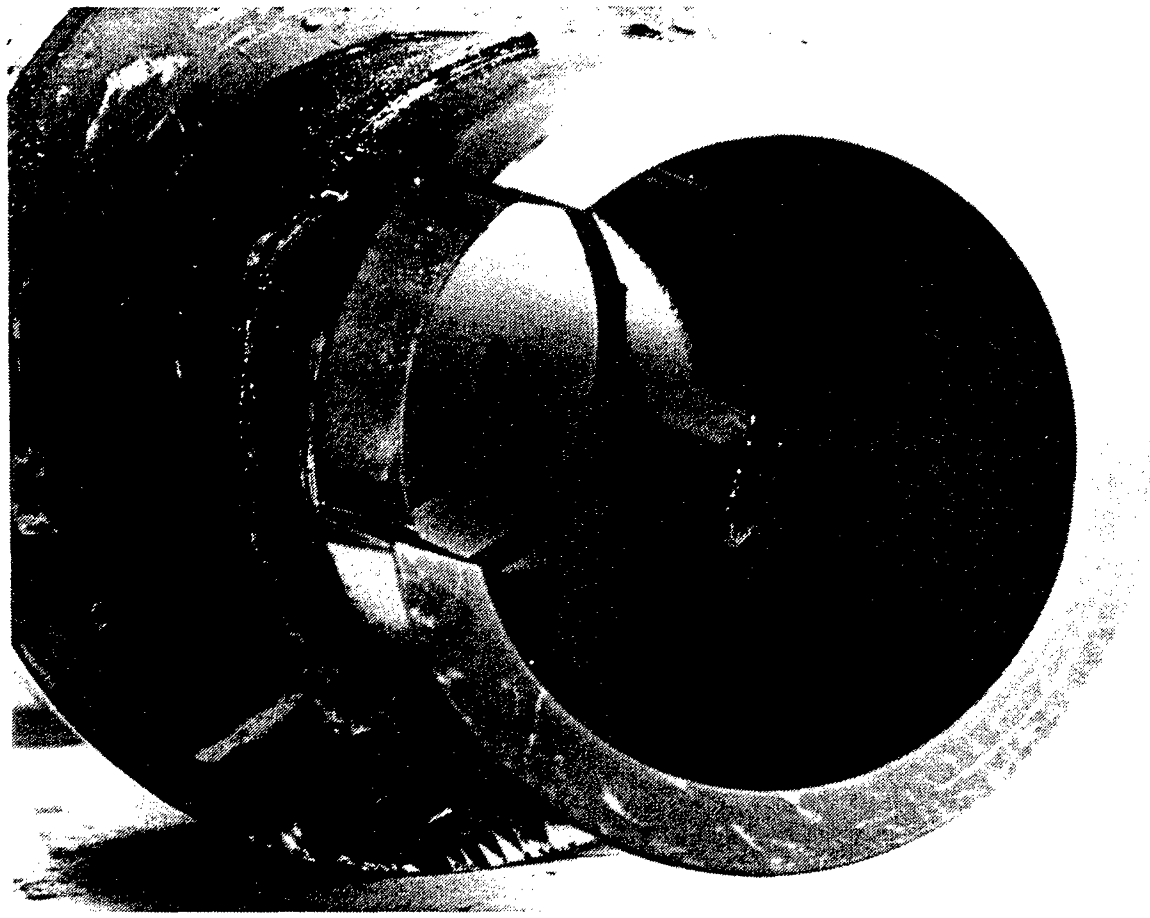


Figure 5-31. SASC Cylinder Bore After Firing with Sialon Pistons (B/N-08)

Table 5-15. Engine Build B/N-08 and Results

Components	Identification	Remarks
SASC Cylinder and SASC Stiffening Ring	C/N-03	Same design as B/N-07
Sialon Pistons with metal ball and socket carrier	P/N-A and B	Same design as B/N-07
Operating Results		
Preliminary Operation: Engine motoring - 15 Hrs.		Piston run-in operated to 1,600 rpm, smooth operation no vibration, compression check - 320 psi @ 800 rpm and 360 psi @ 1,000 rpm, inspection of ceramic components indicated no abrasive wear evident.
Engine Evaluation: Engine Motoring - 8.25 Hrs. Engine Firing - 25.5 Hrs.		Firing operation stable, peak combustion pressure 560 psi @ 1,200 rpm, hot friction horsepower measurement initiated March 14, 1985 after 2.5 hours of firing. Testing terminated March 20, 1985 after successful part load operation.
Cumulative Operating Time:	Motoring/Firing	Firing (Hrs.)
SASC Cylinder Liner/Stiffening Ring	48.75	25.5
Sialon Pistons	48.75	25.5
Build Date: March 8, 1985		

5.5.9. Engine Build B/N-09. After the successful firing of the sialon - SASC ceramic build B/N-08, a hardware modification was implemented replacing the sialon pistons with a new set of SASC pistons.
The SASC pistons
were previously class fit to cylinder C/N-03, thus allowing direct friction comparison to the sialon pistons with other hardware remaining constant. Dimensional and O.D. profile measurement details for the pistons are presented in Appendix G. Dimensional parameters for the SASC pistons were essentially the same as the sialon pistons with less O.D. runout (120 microinches max.).

Preliminary motoring evaluations resulted in an increase of 60 psi compression pressure over build B/N-08. This was a result of adjustments that were made in the piston axial position to compensate for a variance in compression chamber volume due to larger chamfers on each piston crown. After 3 hours motoring a brief firing trial was conducted for a total of 1.5 hours to check combustion pressure.

Firing evaluations were continued over several days accumulating operating time at various speeds and part load. Firing was smooth and stable for a given fuel and load setting. Hot friction horsepower measurements (Table 5-16) were obtained.

Table 5-16. Friction Horsepower for Build B/N-09

Engine Speed (rpm)	Torque (Ft.-lbs.)	FHP
900	6.8/7.1	1.16/1.2
1,000	7.2/7.6	1.35/1.40
1,200	7.75/--	1.77/--
1,300	7.8/8.1	1.93/2.0
1,400	7.5/8.5	2.0/2.26
1,500	8.1	2.3

Average friction horsepower results shown in Figure 5-32 closely follow those obtained for build B/N-07, also containing all SASC components. The slightly higher results for the sialon pistons may be due to the greater piston O.D. runout reducing the nominal running clearance. In each case, the ceramic engine builds repeatably show reductions in friction of 40-50% compared to the metal baseline.

During the course of engine testing, indicator cards were taken using a Kistler pressure pickup mounted in the cylinder opposite the injector. A second pressure pickup was installed in the injector line. Typical indicator cards are shown in Figure 5-33. The three traces displayed are: (1) timing trace, (2) cylinder pressure, and (3) injection line pressure. It can be seen in (b) that after injections were taking place resulting in poor combustion.

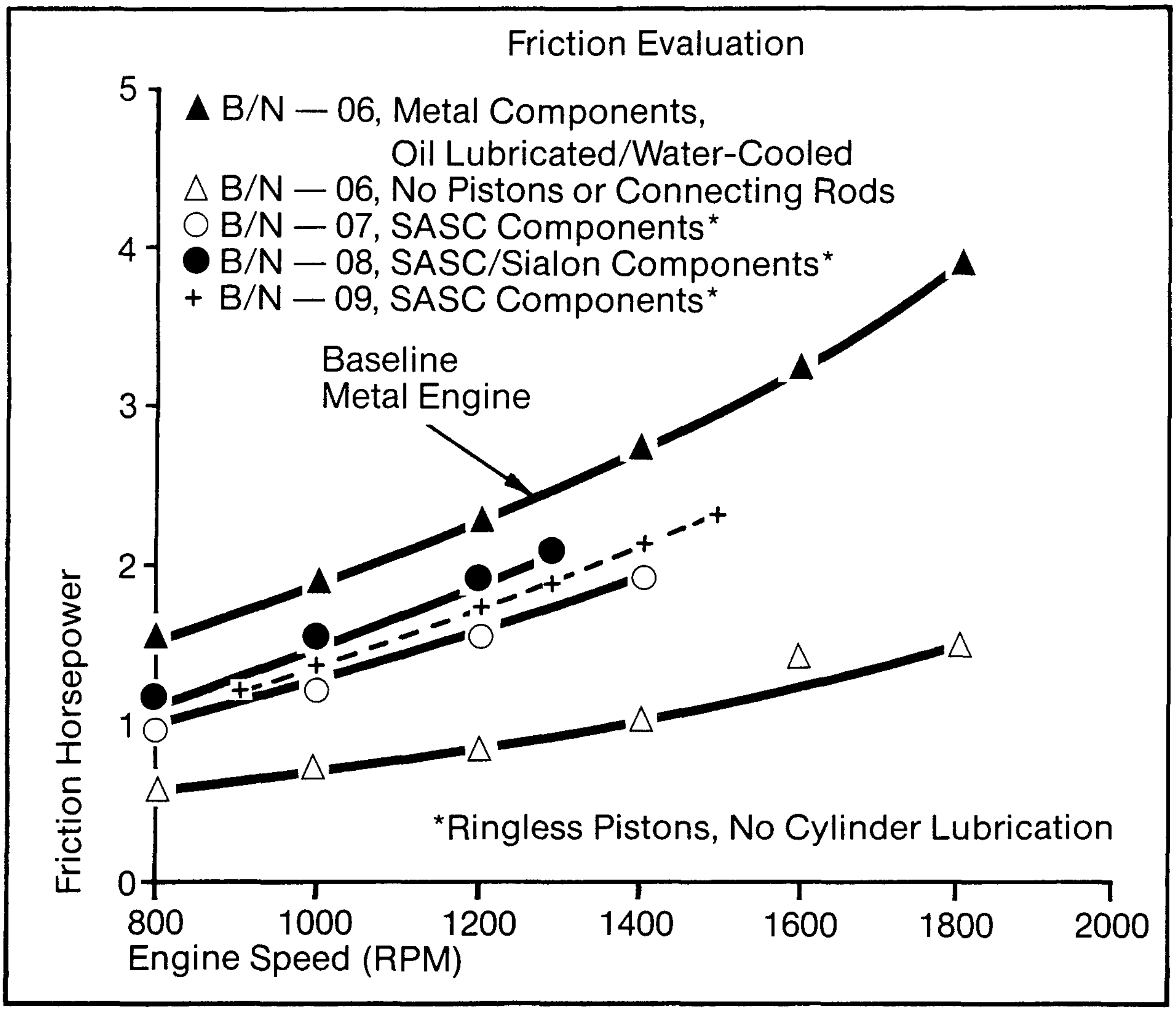
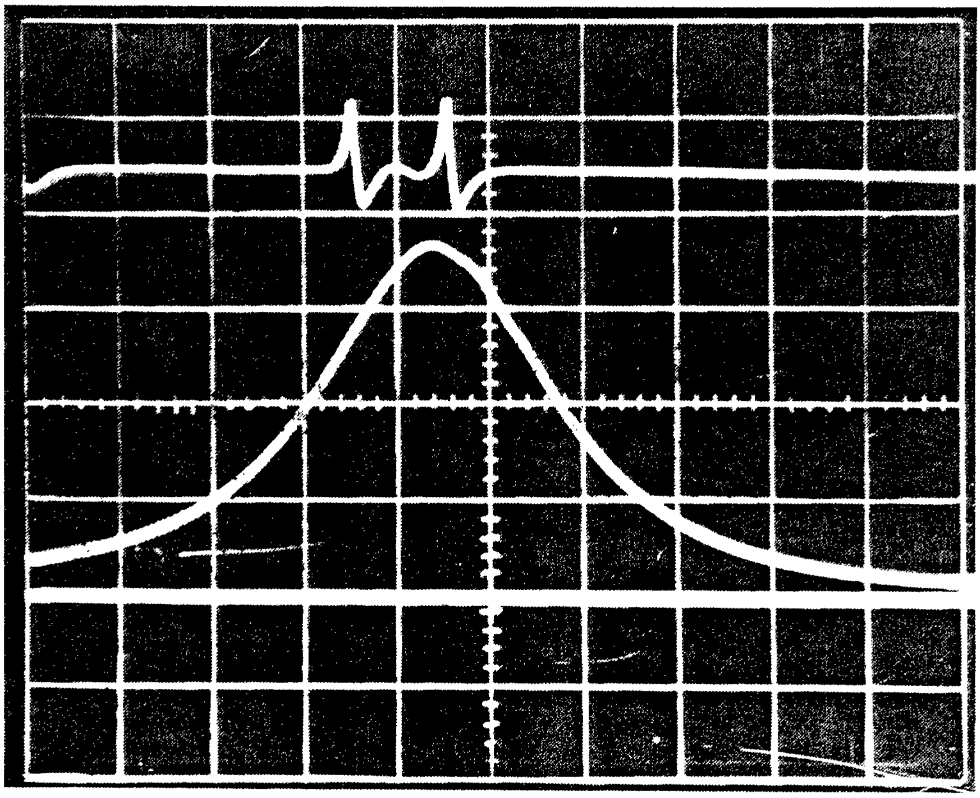
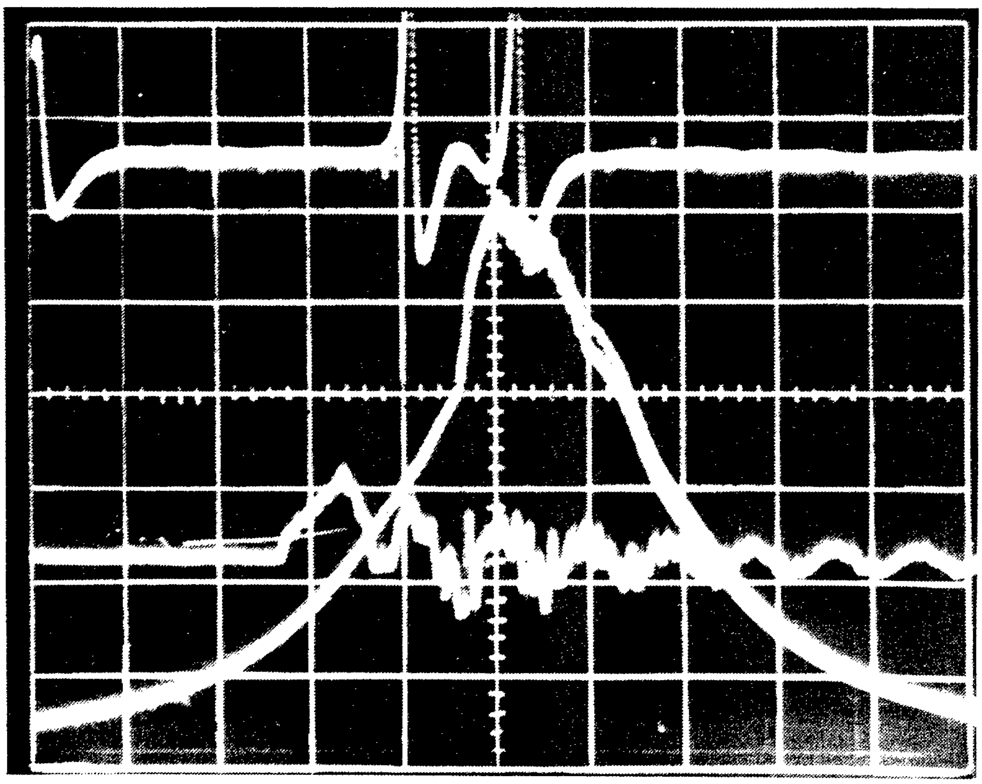


Figure 5-32. Engine Friction Comparison Between SASC Build B/N-09 and Previous Ceramic Builds



(a) Compression Pressure



(b) Firing Pressure and Injection Line Pressure

Figure 5-33. Indicator Card Traces for B/N-09

After successful operation of 50 accumulated hours firing, an evaluation with increased operating load was initiated. Thermal imaging equipment (Hughes Infra-red Thermal Imager) with camera and color video display was located at the Eaton Research and Engineering Center. A photograph of the temperature profile display for the piston is shown in Figure 5-34. The crossed reference lines are focused on the bottom end of the piston skirt indicating a temperature of 424°F. Firing trials were continued increasing engine speed and load recording the temperatures of the end of the cylinder and piston.

After 2.75 hours (62.5 hours cumulative) firing on April 30, 1985, a ceramic hardware failure resulted while operating at 1,400 rpm and an engine output of 2.26 BHP. Temperature measurements just prior to the time of failure indicated a temperature differential of 100°F between the end of the cylinder and the end of the piston (cylinder - 340°F, piston - 440°F). The exhaust gas temperature was recorded at 505°F.

Actual operating temperatures at the piston crown and inner cylinder surface are unknown. Assuming a temperature difference of 100°F existed at failure between the piston crown and the cooler portion of the cylinder at maximum piston travel, the diametral clearance of 0.0005 inches would be closed.

It was concluded that the exhaust piston being the hotter of the two pistons failed due to seizure and resulting tensile stresses causing fracture. A failure analysis was unable to be performed due to the extent of damage to all components. With the exception of the reported bending failure, this conclusion would explain all the other engine component failures discussed, and correlates with the failure analysis from B/N-01 where wear track brittle fracture suggested contact pressure at high load.

A total cumulative operating time summary for the ceramic components is shown in Table 5-17.

Table 5-17. Cumulative Operating Time Summary

Ceramic Components	Combined Motoring/Firing Hrs.	Firing Hrs.
B/N-08 & 09		
SASC Cylinder	116.75	88.0
SASC Pistons	68.0	62.5
Sialon Pistons	48.75	25.5
All Ceramic Builds	242.25	93.75

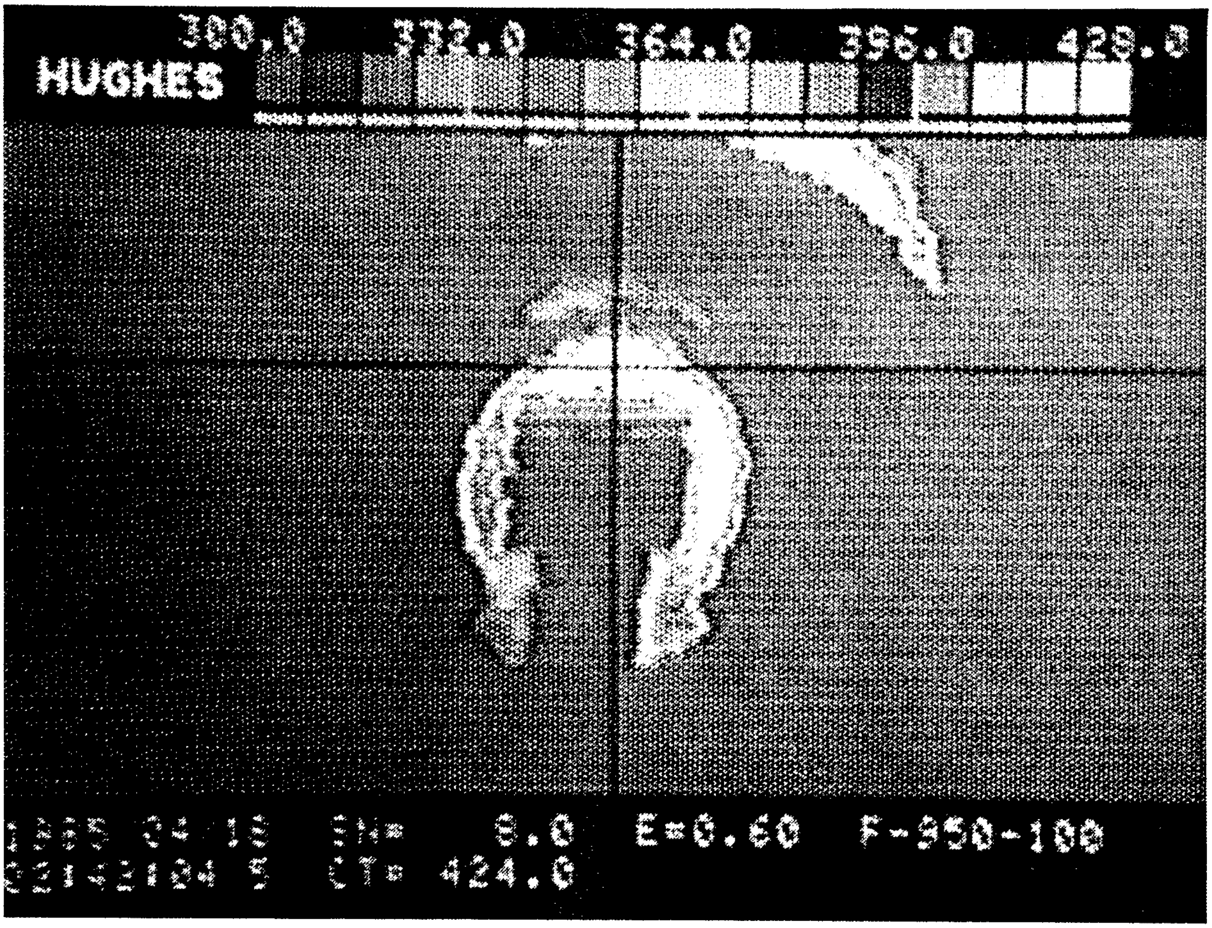


Figure 5-34. Infrared Thermal Profile of SASC Piston End (B/N-09)

Table 5-18. Engine Build B/N-09 and Results

Components	Identification	Remarks
SASC Cylinder and SASC Stiffening Ring	C/N-03	Previously run cylinder assembly from B/N-08.
SASC Pistons with Metal Carrier	P/N-03 and 04	Same design as B/N-08.
<u>Operating Results</u>		
Preliminary Operation: Engine Motoring - 3 Hrs. Engine Firing - 1.5 Hrs.		Compression check - 380 psi @ 800 rpm, combustion pressure check - 530 psi @ 900 RPM.
Engine Evaluation: Engine Motoring - 2.5 Hrs. Engine Firing - 61.0 Hrs.		Firing operation stable; Peak combustion pressure-650 psi @ 1,200 rpm, testing terminated April 30, 1985 - cylinder assembly and piston fractured under firing operation.

Cumulative Operating Time:

	Motoring/Firing Combined (Hrs.)	Firing (Hrs.)
SASC Cylinder Liner/Stiffening Ring (C/N-03)*	116.75	88.0
SASC Pistons	68.0	62.5

Build Date: April 18, 1985

*Includes operating time of Build B/N-08

5.6. Component Finite Element Analysis

Ricardo Consulting Engineers, Ltd., Shoreham-by-Sea, England was funded in a subcontract to perform a finite element analysis for the ceramic piston and cylinder made of SASC, sialon and PSZ. The analysis used inputs for the component thermal, pressure and interia loadings and predicted the resultant component temperatures, displacements and stresses. In addition, a program was written to calculate the probability of failure of the components using the Weibull criterion.

Thermal boundary conditions were calculated by comparison with engines of similar design, constructed of both conventional metals and ceramics. The engine specifications used for the calculation of the boundary conditions were as stated in Table 5-1, except the rated output was over estimated at 13HP. Analyses were made for two piston carrier configurations, one with a undercrown spacer made of mullite, and the other made of steel. Thermal analysis was carried out for both transient and steady state conditions for the piston. Only steady state thermal analysis was performed on the liner, since the piston analysis showed the steady state thermal load was the most severe.

It was assumed for this analysis, as an extreme case, the wall temperatures were 500-700°C. The assumption that the boundary conditions remained unchanged with changing wall temperature may not be valid.

5.6.1. Results of Finite Element Analysis. All the failure predictions show the stresses due to the firing loads are low and insignificant compared to the thermal loads for both the piston and the cylinder.

The stresses and distortions of the sialon components are very similar to those for SASC. The inclusion of the mullite spacer for the sialon and SASC causes higher piston temperatures, and increases the thermal expansion of the crown. The PSZ results are least affected since PSZ is a good thermal insulator.

Predicted failures show that the piston should be adequately strong for sialon and SASC with predicted failure rates of 2 in 10,000,000. Due to the higher thermal gradients developed in PSZ, a failure of 2% was predicted.

The SASC and sialon cylinders expand keeping the bore circular, however, the PSZ liner becomes elliptical which would cause sealing problems as the piston remains circular.

5.6.2. General Conclusions of Finite Element Analysis.

- All material candidates should work in a running engine provided materials meet specifications. The PSZ material specifications are particularly crucial.
- The pistons expand more than the liner so adequate clearance must be allowed when the components are cold to avoid seizure when running.
- The engine must be warmed up slowly to avoid the piston crown expanding more quickly than the liner.

The summary information presented in this section is only a brief review of a more detailed and comprehensive report prepared by Ricardo Consulting Engineers.[2]

5.7. Acousto-Optic NDE Study

DHR, Inc., McLean, Virginia, in collaboration with consultants at Georgetown University's Ultrasonics Laboratory were funded in a subcontract to investigate the non-destructive evaluation of artificially induced flaws in sintered alpha silicon carbide test samples by an experimental acousto-optic technique. This technique involved the non-specular reflection profile of an ultrasonic beam incident at a critical angle called the Rayleigh angle.

Sintered alpha silicon carbide (SASC) test specimens with artifically induced surface flaws were supplied for evaluation. Details of samples provided are given in Appendix I.

The objective of the subcontract was to establish the required experimental parameters for SASC and perform the following tasks:

- Detection and characterization of microstructural defects by:
    - Calculating and experimentally verifying changes in non-specular features of the reflected beam profile as a result of local variation of the sound velocity due to the presence of near-surface microstructural defects in a SASC substrate.
    - Characterization of defects which will include identification of defect size, defect position, and the local sound velocity.
- Detection and characterization of linear finite cracks by:
    - Calculating and experimentally verifying changes in the beam profile non-specularly reflected at the Rayleigh critical angle due to the presence of a small linear crack near the surface of a SASC substrate. Characterization of cracks involving size and position of cracks.
- Resolution of surface stresses and stress gradients.

In carrying out this work, the effects of frequency, intensity, beam width and other important variables were to be studied.

5.7.1. Experimental Parameters Determination. Theoretical and experimental efforts were undertaken to determine the optimal excitation frequency and incident beam width for SASC. Various combinations of transducer frequency, beam width and focal length were attempted with unpredictable success to produce non-specular effects with any degree of resolution.

A Rayleigh mode was obtained on a 2x2 inch SASC plate showing a slight displacement of the reflected beam profile. The Rayleigh angle was measured to be 12.6°±0.2. Reducing the width of the incident beam for

better resolution (down to 3mm) significantly altered the position and resolution of the reflected profile. Further experimentation indicated the best available excitation frequency that would be most sensitive was 20MHZ.

5.7.2. Results of Acousto-Optic NDE. Acousto-optic NDE studies resulted in limited progress to establish optimum experimental parameters for sintered alpha silicon carbide. Resolution of the overall system remained a problem due to the beam width and the small angle of incidence at the Rayleigh angle. The Rayleigh angle showed a dependence on both beam width and frequency. It was concluded the most pronounced nonspecular effects require the smallest possible beam diameter to irradiate the smallest possible sample area to produce a nonspecular reflection pattern distinct enough to be recognized and characterized.

5.8. Piston Injection Molding Study

Task III of the contract was initiated after receiving injection molding tooling designed for a dimensionally close SASC piston to those used in the engine testing phase of the program.

5.8.1. Tool Design. The requirements of fabricating a ceramic piston employing a mass production technique suggested the gate be located on the piston inner surface, and large enough to minimize flow lines. The tool, therefore, was designed to inject the ceramic mix at the undercrown location of the piston cavity. A heated nozzle was also utilized to maintain mix stream fluidity and provide good flow of the mix into the sprue bushing.

5.8.2. Discussion of Fabrication Results. Initial molding trials were unsuccessful due to greater than anticipated hydraulic pressure dislodging the sprue bushing. The sprue bushing retainer was reinforced, and a second molding trial conducted to establish appropriate molding parameters. With the remaining molding compound, a total of 46 visually acceptable pistons were injection molded. Thirty-two (32) pistons were processed through binder removal (Process A) and sintered in two separate furnace runs. The balance of the 14 pistons were processed through the binder removal step (Process B) and all sintered in one furnace run. The process results are presented in Table 5-19.

Table 5-19. Injection Molded Pistons - Process Results

Process	Quantity	Results
Injection Mold	46	All pass visual inspection
Binder Removal		
- Process A	32	12 cracked, 20 pass
- Process B	14	14 pass
Sinter		
- Group 1 (Process A)	10	6 cracked, 2 internal defects; 2 pass x-ray inspection
- Group 2 (Process A)	10	5 cracked, 5 pass x-ray inspection
- Group 3 (Process B)	14	5 cracked, 9 pass x-ray inspection

Pistons which passed x-ray examination and showed internal defects were submitted for bulk wave ultrasonic inspection. Ultrasonic inspection verified the presence of internal defects as observed by x-ray. Only 2 pistons were judged to have no detectable flaws by either technique. All other pistons had ultrasonic inspection indications of microstructure problems (presumably porous regions) or hairline cracks in the crown underside. The potential porous regions or hairline cracks were generally located in the gated region.

Ten (10) pistons, including 2 with no detectable flaws and eight with various defects recorded were transferred to TACOM for further study.

5.8.3. General Conclusions of Injection Molding Study.

- Preliminary process parameters were acceptable to successfully fabricate a heavy wall piston, but require further process development.

- The major defects due to cracked pistons were located near the sprue region, and appeared to be molding related.

- The cause of major defects was unresolved, but would likely be corrected with further process experiments.

LIST OF REFERENCES

[1] Timoney, S. and Flynn, G., "A Low Friction, Unlubricated SiC Diesel Engine," SAE Paper No. 830313 (1983).

[2] Page, L.J., "Finite Element Analysis of Components From a Ceramic Engine," Ricardo Consulting Engineers, Sussex, England (1984).

APPENDIX A

ORIGINAL SASC COMPONENTS

DESIGN FOR ENGINE BUILD B/N-01

- Cylinder Liner/Outer Housing
- Piston/Ceramic Carrier Assembly

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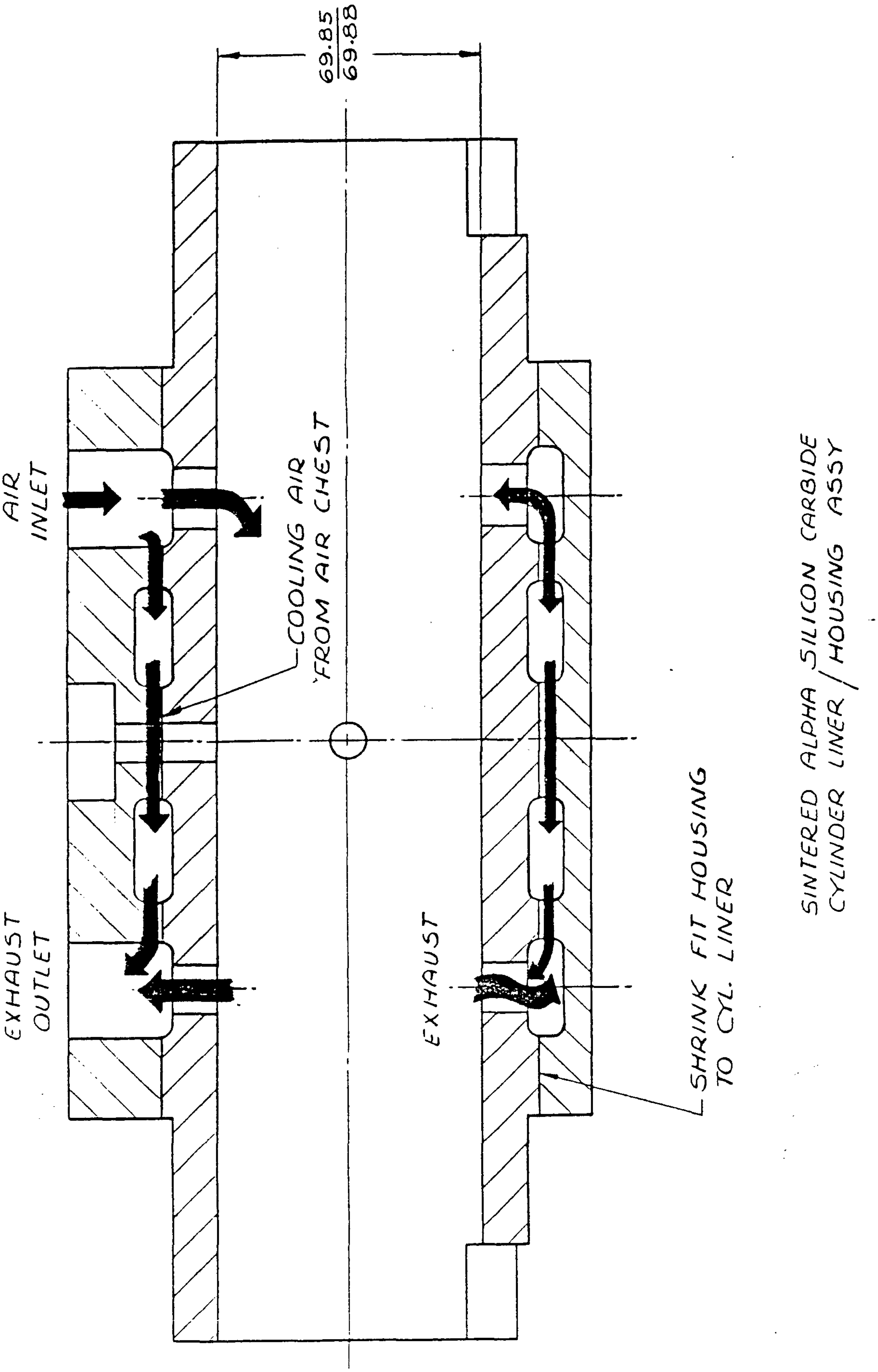
69.85
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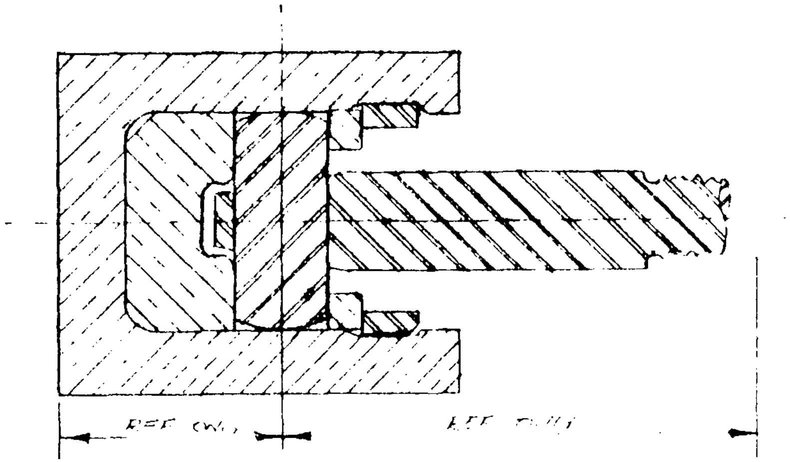
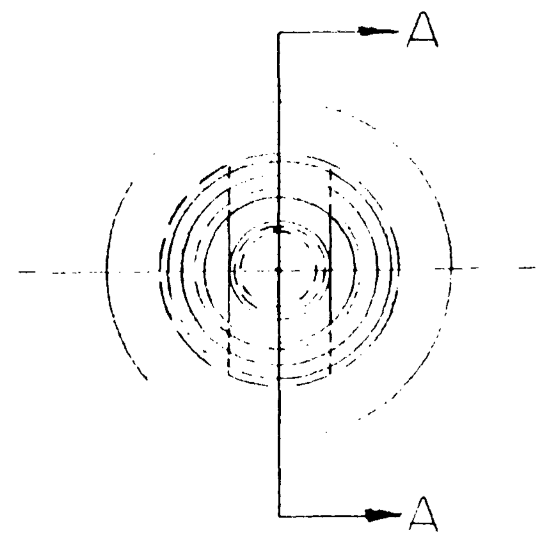
CYLINDER LINER / HOUSING ASSY



SECTION A-A



NOTE:
REF. DIMENSIONS MUST
MATCH TIMONEY ENGINE

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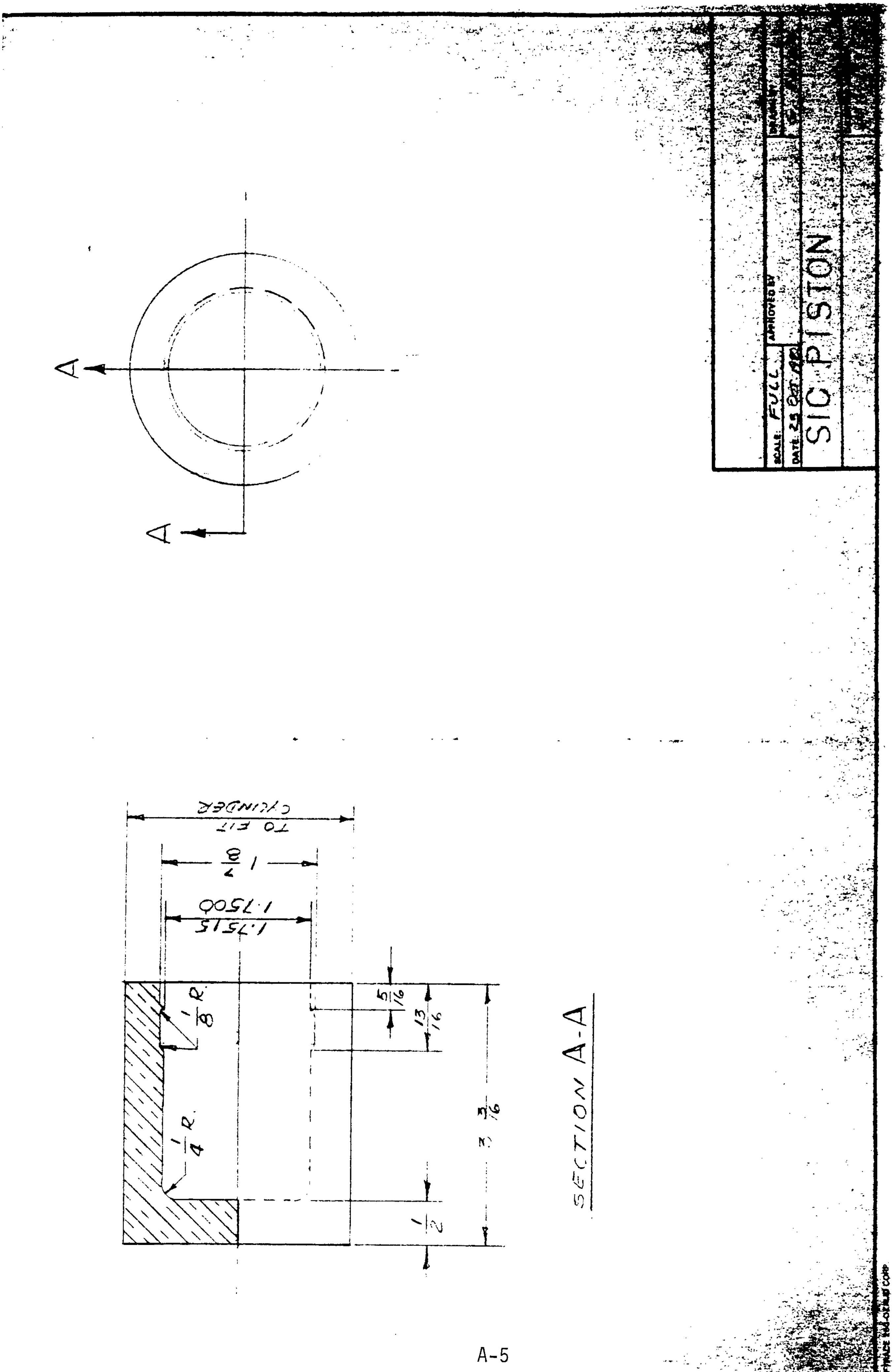
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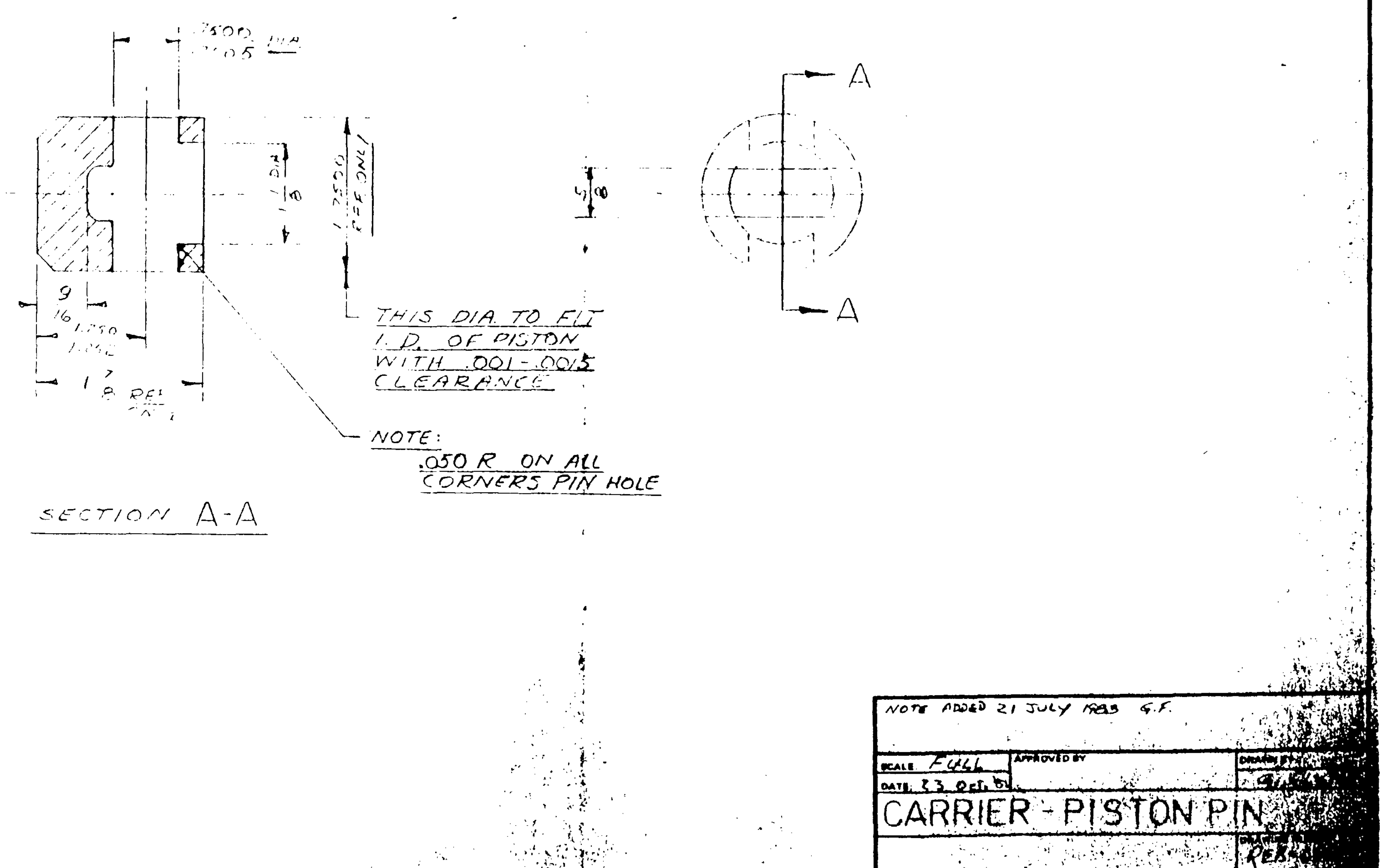
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NOTE:
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CORNERS PIN HOLE
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APPENDIX B

FRACTOGRAPHY ANALYSIS OF SASC CYLINDER FAILURE IN ENGINE BUILD B/N-01

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FAILURE ANALYSIS
(BUILD B/N-01)

The SASC cylinder/housing (C/N-00) consisted of two isopressed cylinders fit together and sintered as a monolithic assembly. The joining technique results in a residual stress state where the tangential stresses are tensile in the outer housing and compressive in the cylinder liner.

A photograph of the failed cylinder is shown in Figures B-1 and B-2. A magnified view of the probable failure origin is shown in Figure B-3. The failure site is near the fuel injector port at the interface between the cylinder liner and outer housing. The assembly method produces maximum tensile stresses at the I.D. of the outer housing causing a high probability of failure in this region.

SEM micrographs of the wear track on the I.D. of the cylinder liner shown in Figures B-4 and B-5 indicates scoring and abrasive wear with areas of brittle fracture.

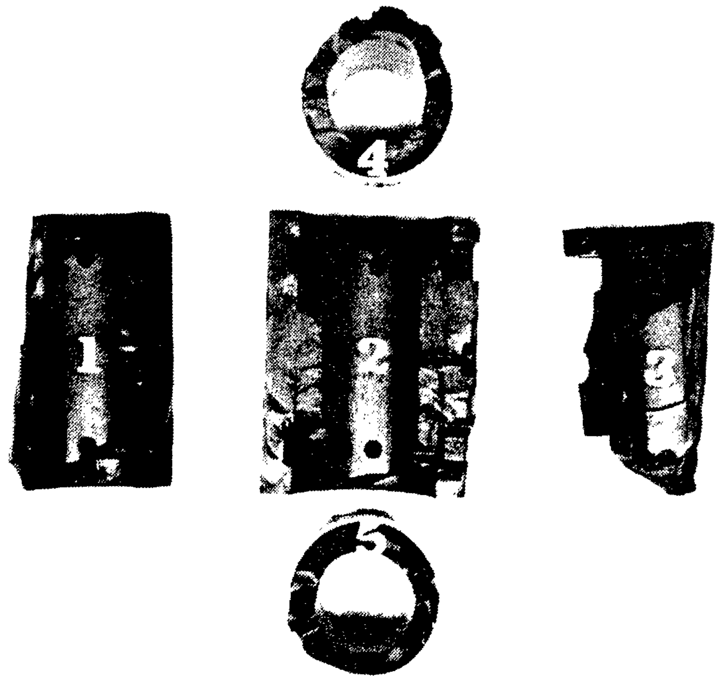
Conclusive evidence of the primary fracture origin and reason for failure could not be established due to the extensive fracture surface and numerous fragmented pieces. However, the following observations and conclusions are drawn:

1. Property measurements are characteristic for the material.

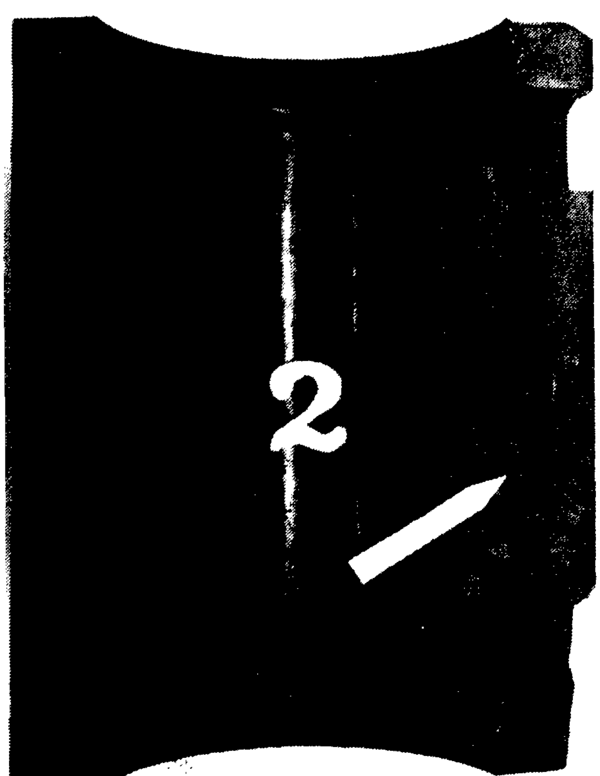
2. Areas of incomplete bonding exist between the cylinder liner and outer housing.

3. Abrasive and brittle fracture wear is observed in the wear track on the cylinder bore suggesting contact pressure at high load.

4. A probable failure origin site was identified near the fuel injection port at the region of high residual tensile stress.

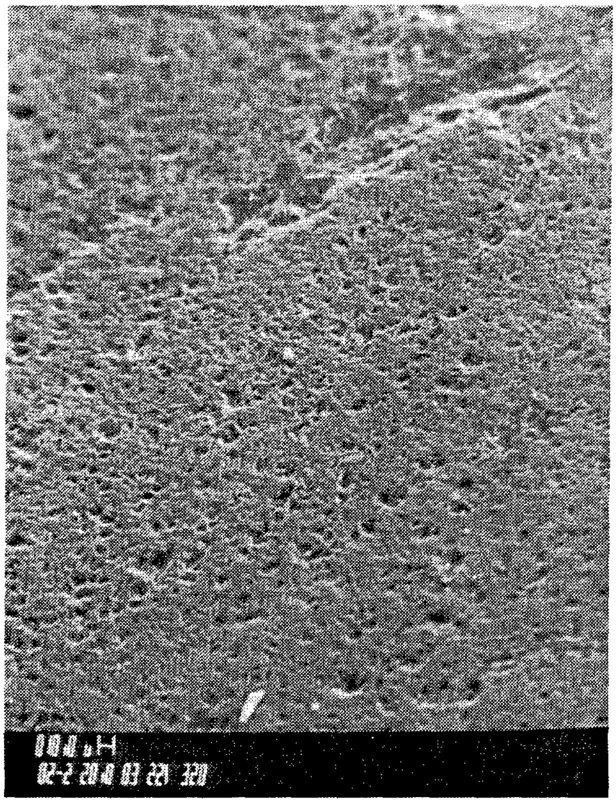


B-1. Fractured Cylinder Sections



B-2. Closeup of Segment 2 - Arrow Indicates Identified Failure Origin

B-3. Magnified (3.5X) View of Failure Origin in Outer Housing at the I.D.



B-4. Wear Track on Cylinder Bore

B-5. Magnified View of Wear Track Indicating Brittle Fracture

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APPENDIX C

REDESIGNED SASC COMPONENTS
FOR ENGINE BUILD B/N-05

- SASC Cylinder and Pistons
- SASC Stiffening Ring
- Cylinder Assembly
- Piston Profilometry Curves
- Metal Piston Carrier

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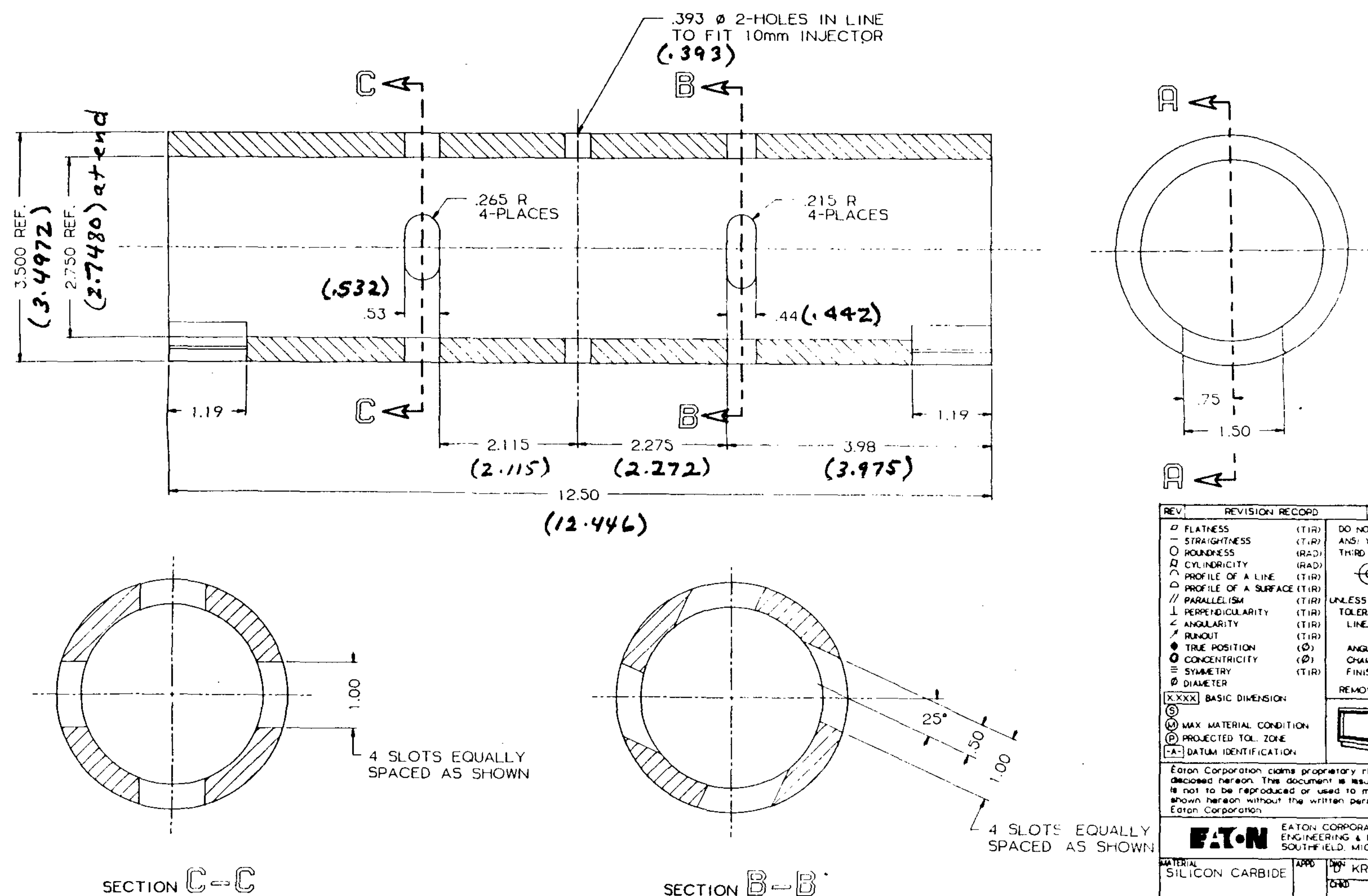

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- STRAIGHTNESS (TIR)
- ROUNDNESS (RAD)
- CYLINDRICITY (RAD)
- PROFILE OF A LINE (TIR)
- PROFILE OF A SURFACE (TIR)
- PARALLELISM (TIR)
- PERPENDICULARITY (TIR)
- ANGULARITY (TIR)
- RUNOUT (TIR)
- TRUE POSITION (Ø)
- CONCENTRICITY (Ø)
- SYMMETRY (TIR)
- DIAMETER
- X.XXX BASIC DIMENSION
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- Ⓜ MAX MATERIAL CONDITION
- Ⓟ PROJECTED TOL. ZONE
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DO NOT SCALE DRAWING
ANSI Y 14.5-1973 APPLIES
THIRD ANGLE PROJECTION

UNLESS OTHERWISE SPECIFIED
TOLERANCES
LINEAR .XX = ±.01
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ANGULAR ±0°30'
CHAMFER ±5°
FINISH SURFACES 125

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MATERIAL SILICON CARBIDE	APPD	DWN KRZYSIK	DATE 2-1-84
		CHKD	DATE
PROCESS AND/OR HEAT TREAT	APPD	APPD	DATE
		PROJ NO 3407-02	PL NO
DIMENSIONAL UNITS INCH	TITLE CYLINDER		
ORIG SCALE 1/1	ITEM NO	LAST REV	PART NO 57346-D	SHEET /

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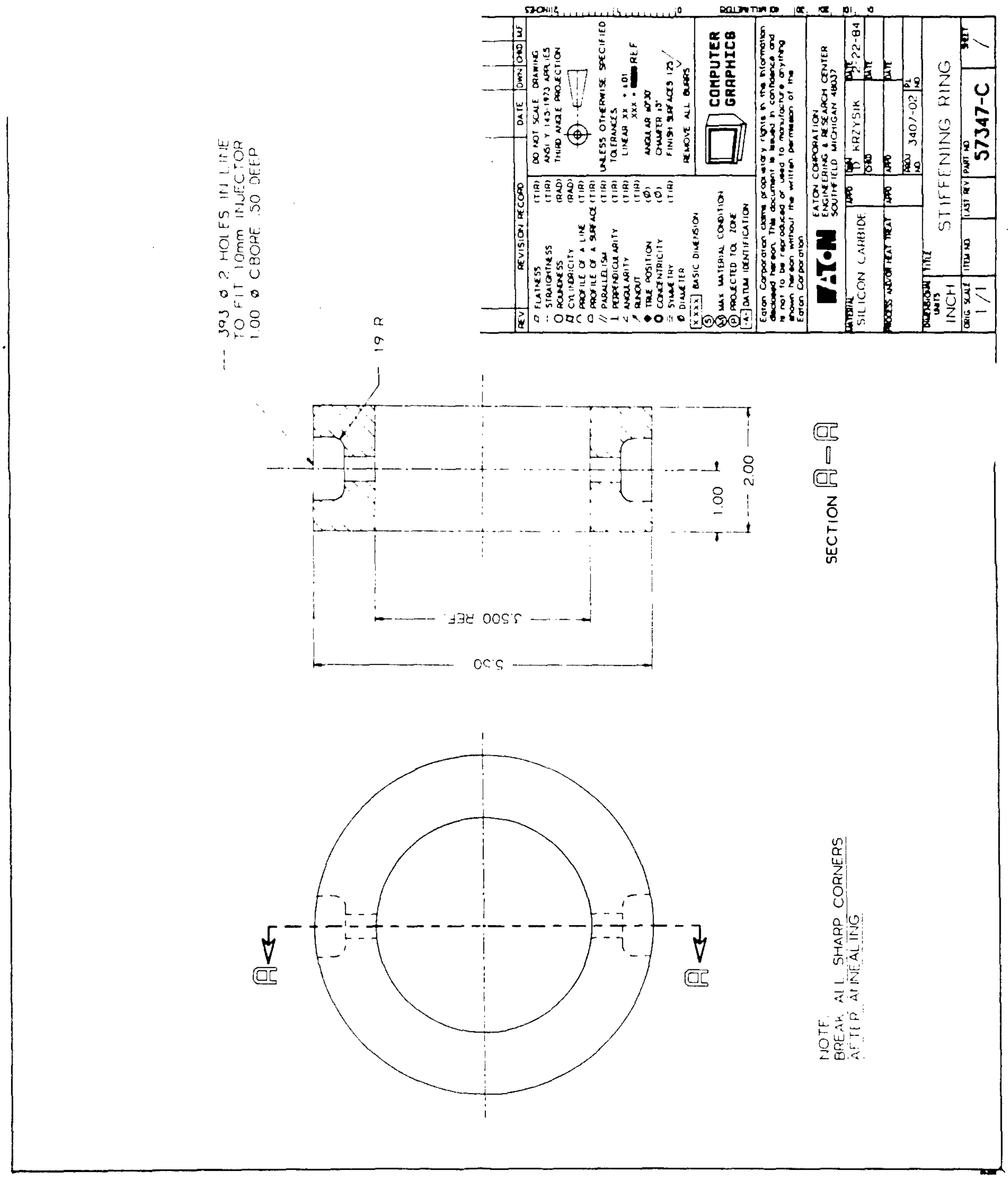
MILLIMETERS 40 30 20 10 0

NOTE: Values in parenthesis are measured dimensions.



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3.500 REF
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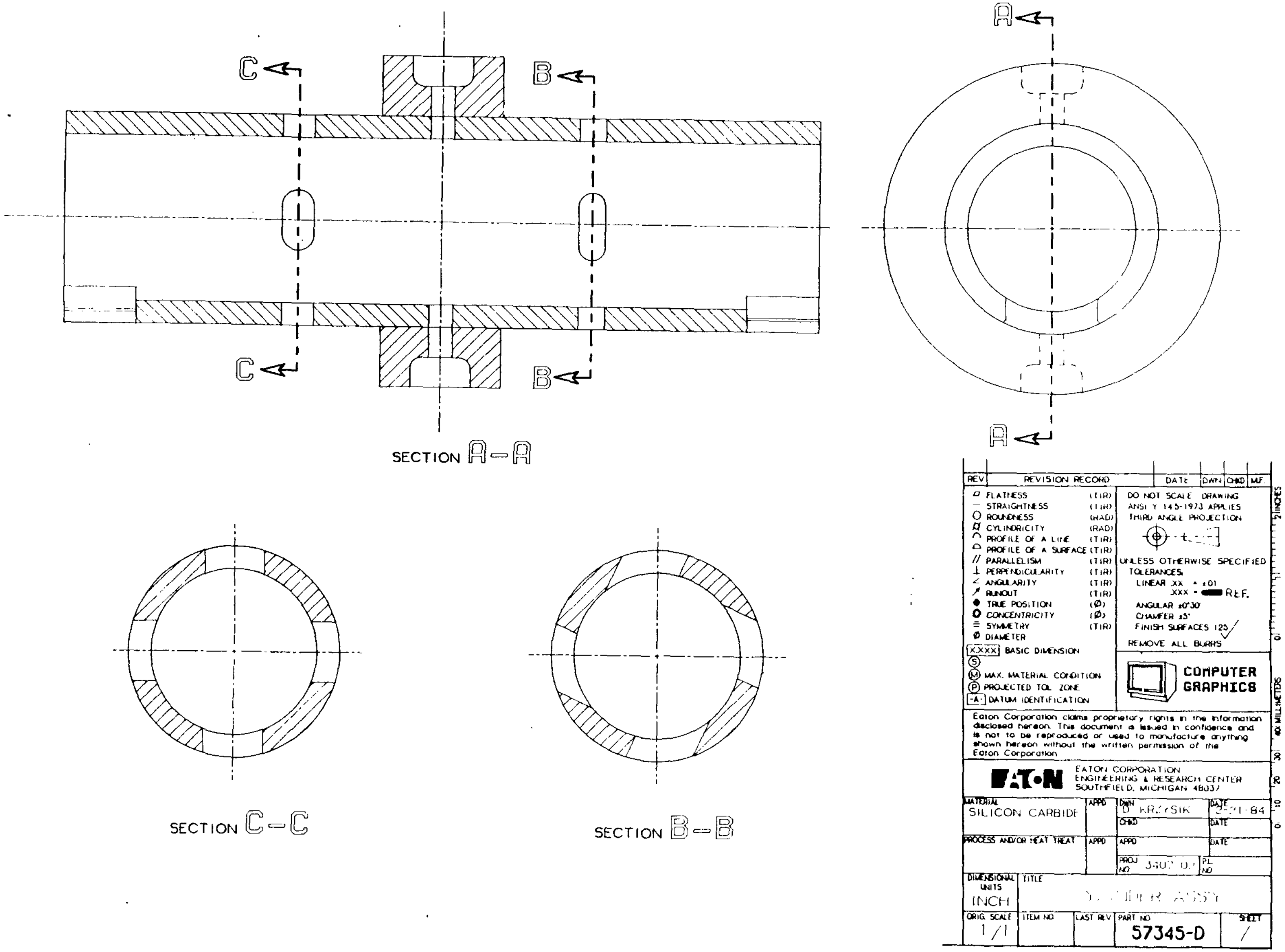
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PROJECTED TOL ZONE
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UNLESS OTHERWISE SPECIFIED
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XXX ± REF.
ANGULAR ±0°30'
CHAMFER ±5°
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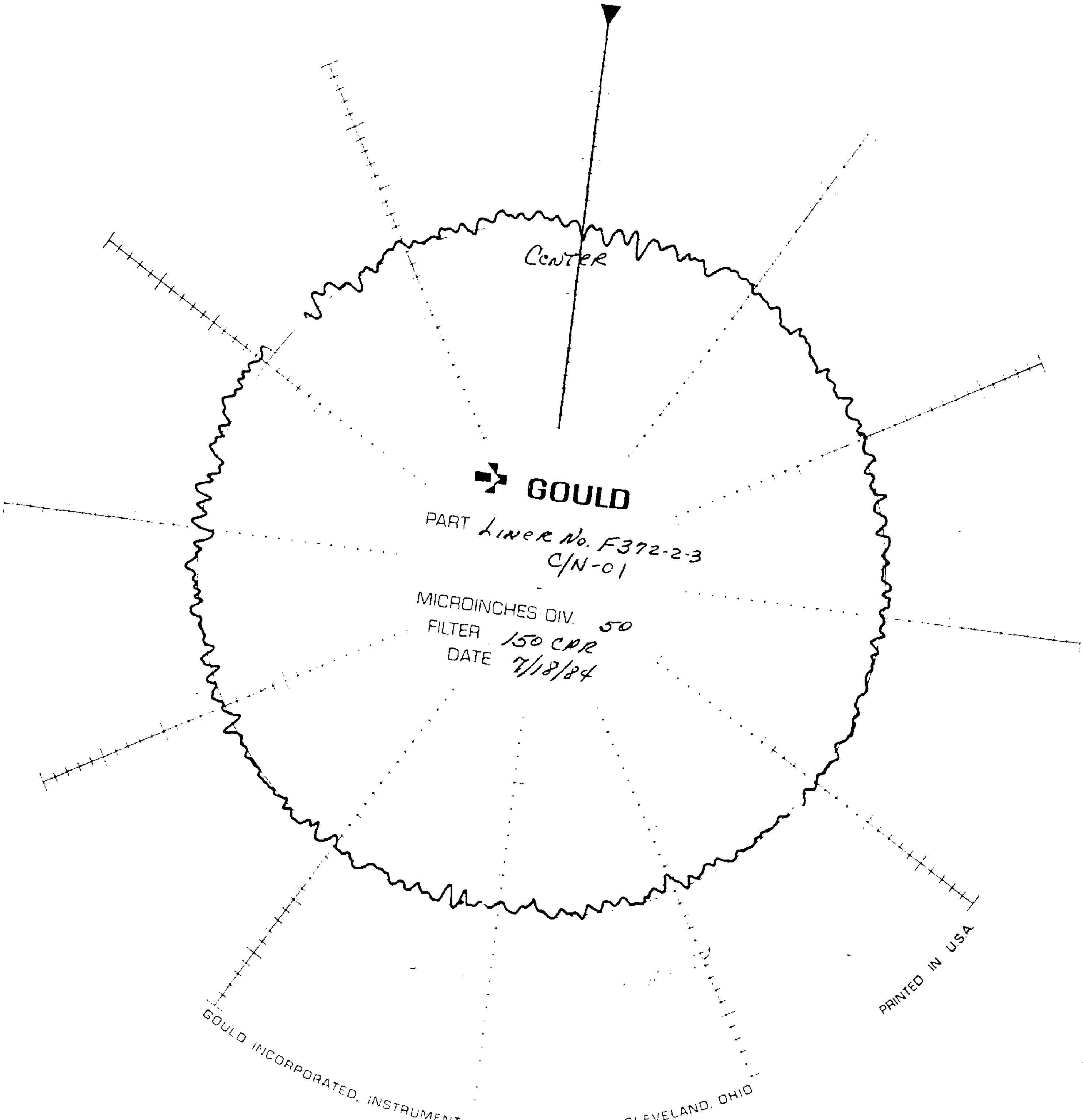

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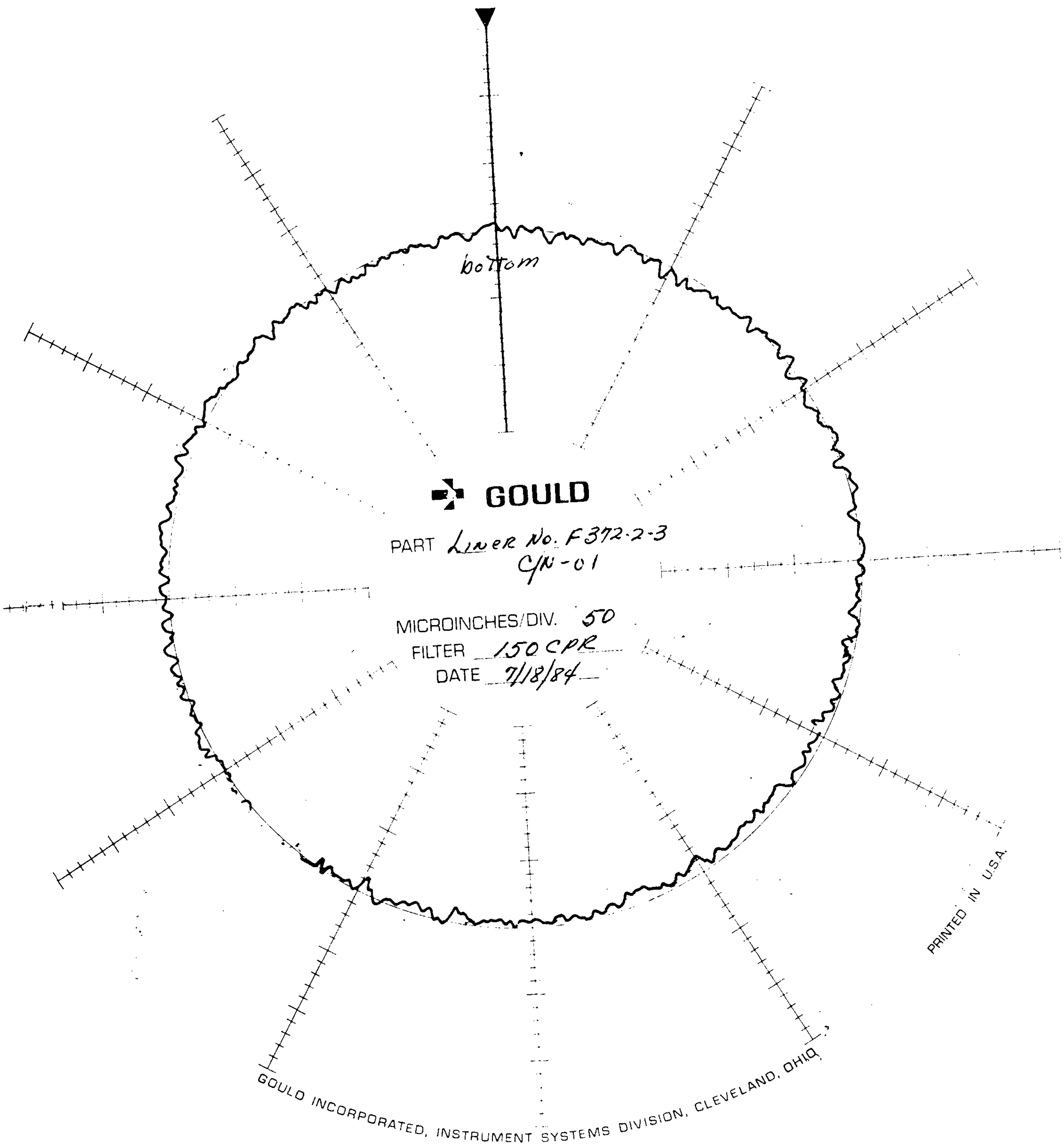
GOULD INCORPORATED, INSTRUMENT SYSTEMS DIVISION, CLEVELAND, OHIO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C/N-01
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FILTER 150 CPR
DATE 7/18/84
PRINTED IN U.S.A.
GOULD INCORPORATED, INSTRUMENT SYSTEMS DIVISION, CLEVELAND, OHIO

EATON Engineering & Research Center

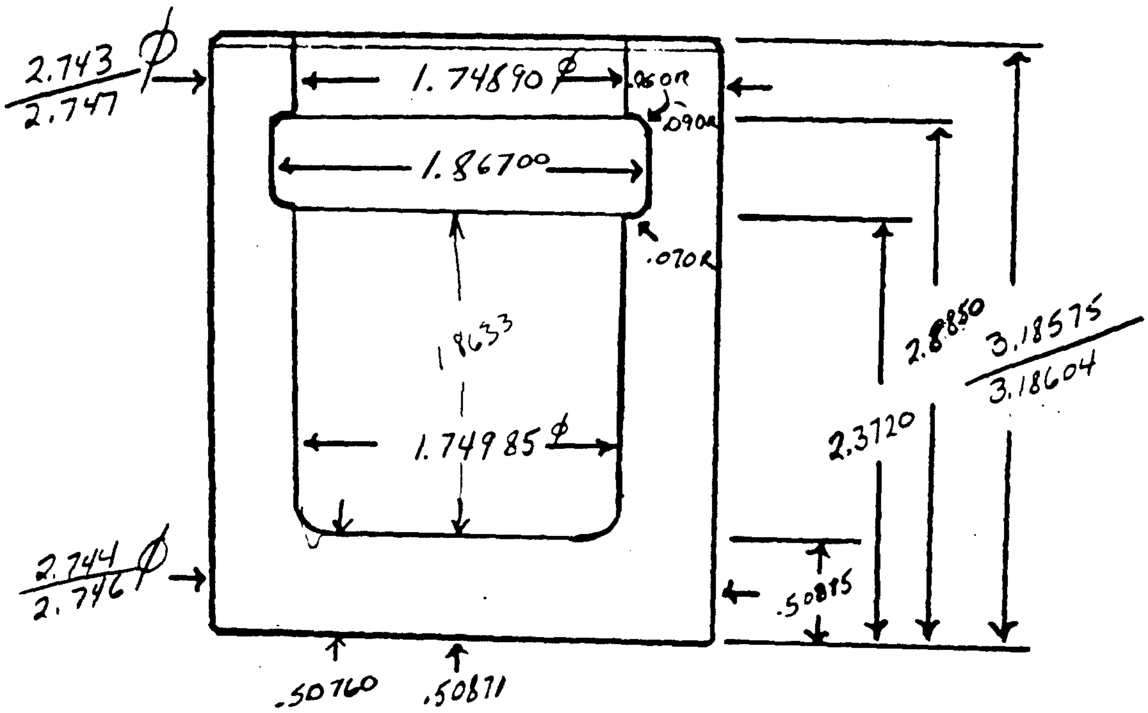
COMPONENT QUALITY RECORD

PART NO. 372-1 P/N-6 PROJECT NO. 3407-02

PART DESCRIPTION: PISTON S/N 6

INSPECTED BY: J. A. OLSON DATE 5-21-84

INTENDED USE OF COMPONENT ASSEMBLY:



E·T·N

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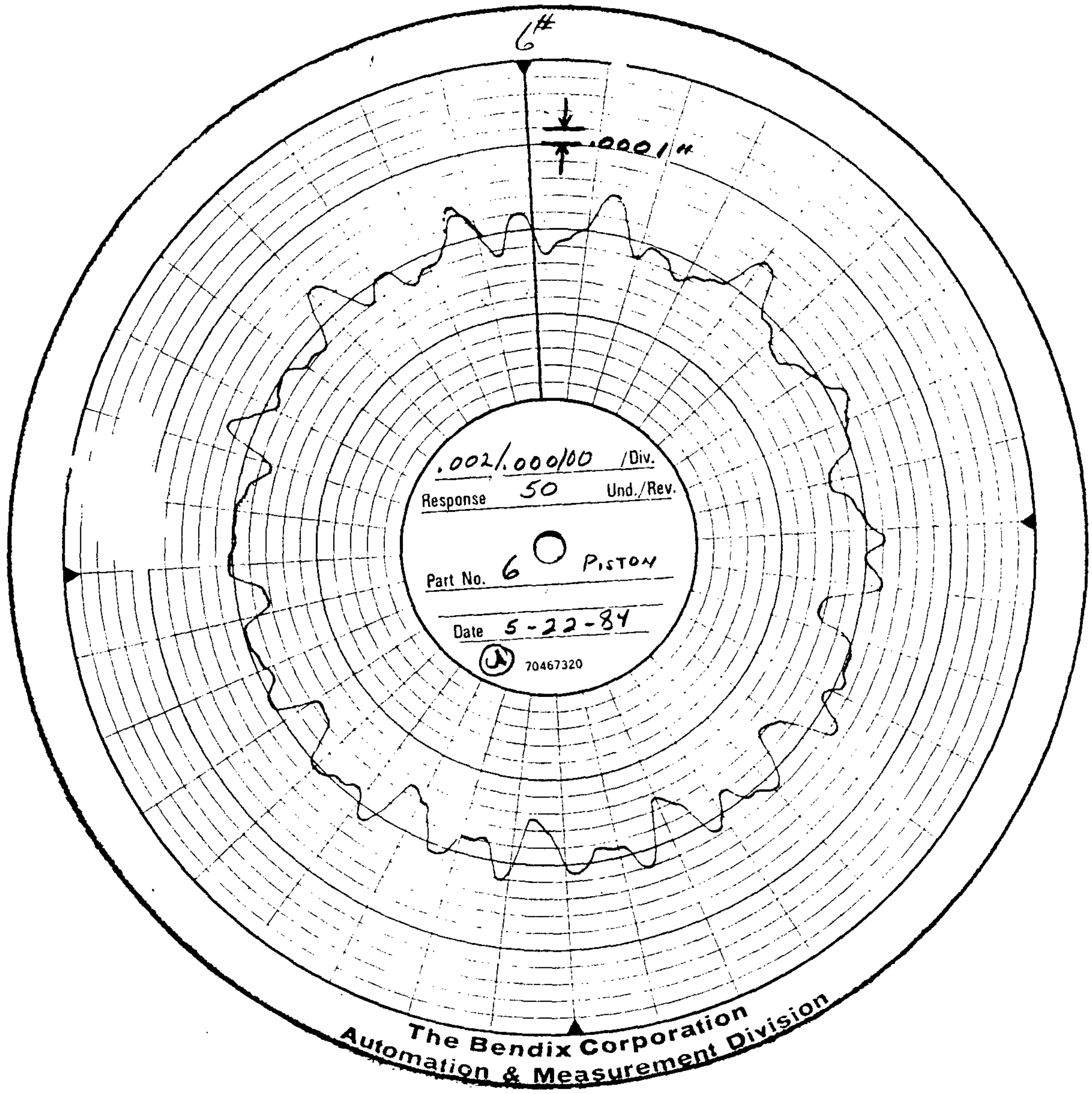
Engineering & Research
Center

Component Quality Record

Part No. 372-1 P/N-6 Rev. ______ Project No. 3407-02 Date 5-22-84
Part Name PISTON Lot ______ Qty. 1
Inspected By: J A OLSON P.O/W.O. ______
Assembly No. ______ Engineer ______



E39-84B (9/80)

EATON Engineering & Research Center

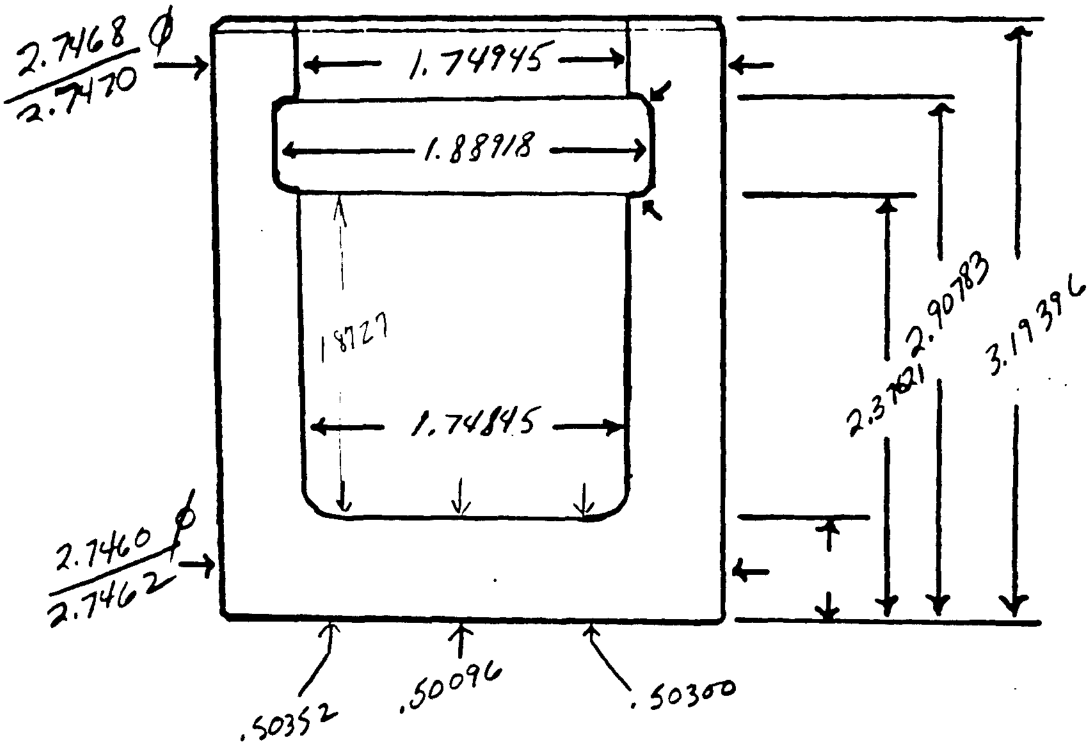
COMPONENT QUALITY RECORD

PART NO. 372-1 P/N-7 PROJECT NO. 3407-02

PART DESCRIPTION: PISTON S/N 7

INSPECTED BY: J.A. OLSON DATE 5-21-84

INTENDED USE OF COMPONENT ASSEMBLY:

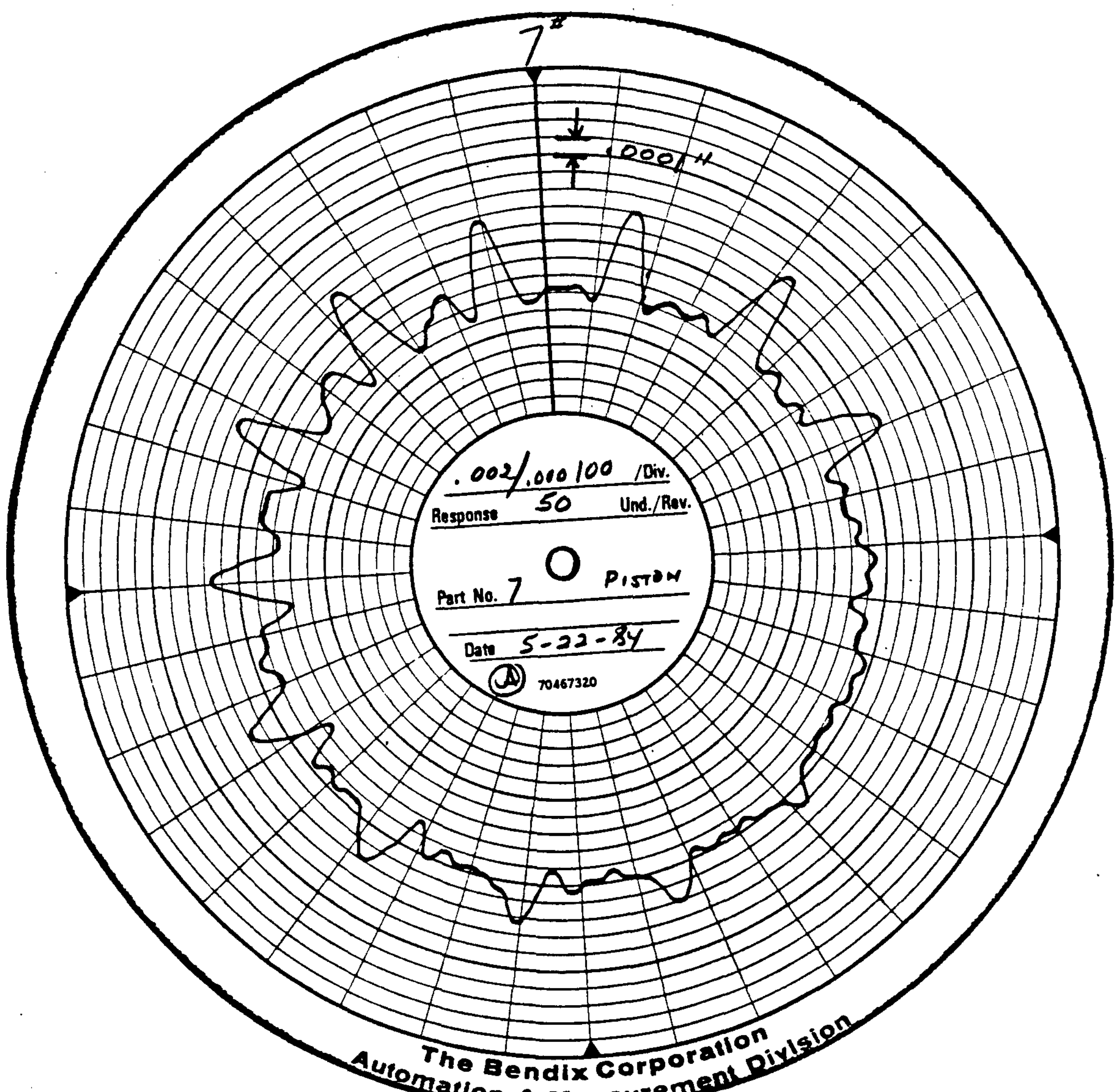


EATON

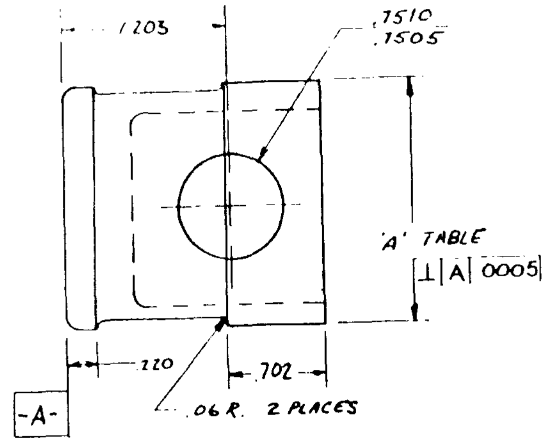
Eaton Corporation
Engineering & Research
Center

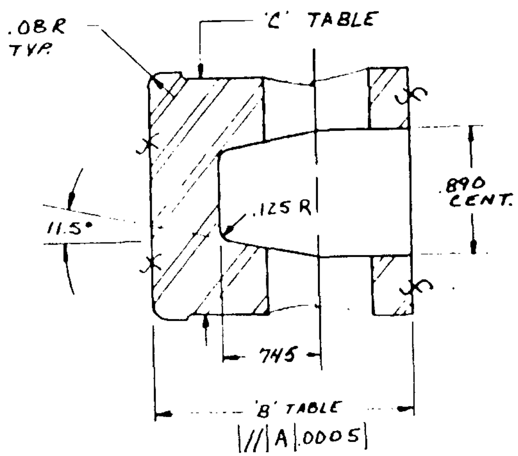
Component Quality Record

Part No. 372-1 P/N-7 Rev. ______ Project No. 3407-02 Date 5-22-84
Part Name PISTON Lot ______ Qty. 1
Inspected By: J A OLSON P.O/W.O. ______
Assembly No. ______ Engineer ______



E39-84B (9/80)

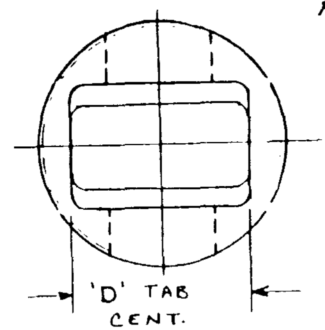




P/N	'A' DIA	'B' OAL	'C' DIA	'D' WIDTH
2	17497 1 7492	1.8653 1.8658	1.670	1375
5	1.7247 1.7242	1.866 1.8665	1.645	1.350

NOTES

1. MAT'L CARPENTER LOW EXPANSION '42'
2. TO FIT CARBORUNDUM PISTONS 2-F372 AND 5-F372
3. REF. CARBORUNDUM PRINT # REC-6070-A
4. ONE EACH REQ'D
   P/N 2
   P/N 5
5. 3 PLACE DIM ARE ± .005



PISTON CARRIER

PROJ 3407-02

CARPENTER TECHNOLOGY CORPORATION

CARPENTER STEEL DIVISION

CarTech

TECHNICAL DATA

CARPENTER LOW EXPANSION "42"

(K94101)

Type analysis:

Carbon	**0.05% max.**
Manganese	**0.4%**
Silicon	**0.2%**
Nickel	**41%**
Iron	**Balance**

DESCRIPTION:

Carpenter Low Expansion "42"® is a 41% nickel-iron alloy which has a virtually constant low rate of thermal expansion at temperatures up to about 650° F (343° C). It is used for applications in which relatively low expansion is necessary to prevent errors or variations due to changes in temperature or those in which Low Expansion "42" is used in conjunction with a high expansion element such as in thermostats or thermo switches where temperatures may go as high as 650° F (343° C).

Carpenter Low Expansion "42" is manufactured to ASTM F30-77 and fully conforms to the requirements of this specification.

PHYSICAL CONSTANTS:

Specific gravity 8.12
Density — lb/in^3 .... 0.293

Coefficient of thermal expansion: as annealed

Temperature		Coefficient	
77° F to	25° C to	10^{-6}/° F	10^{-6}/° C
212	100	2.57	4.47
392	200	2.54	4.58
572	300	2.71	4.61
662	350	2.78	5.02
752	400	3.14	5.70
842	450	3.83	7.03
932	500	4.32	7.78
1112	600	5.50	9.90
1292	700	6.12	11.00
1472	800	6.66	11.99
1652	900	7.10	12.78

Electrical resistivity
ohm-cir mil/ft 430
microhm-mm 710
Specific heat
Btu/lb • °F 0.12
kJ/kg • K 0.50
Thermal conductivity
Btu-in/ft^2/hr/°F (68/212° F) 74.5
W/m • K (20/100° C) 10.7
Curie temperature .... 716° F (380° C)
Melting point .... 2600° F (1425° C)

WORKING INSTRUCTIONS:

Blanking and Forming: For clean blanking of Carpenter Low Expansion "42", a Rockwell hardness of about B 90 is suggested. Where any sharp bends are involved in forming finished parts from strip or rods, a hardness of not over B 93 is suitable.

Cold Heading: Carpenter Low Expansion "42" may be swaged or cold upset.

Plating: It can be electroplated or zinc coated by the usual methods for ferrous alloys.

Grinding: A silicon carbide wheel is desirable, preferably a soft wheel which will wear without loading. For finish grinding, a satisfactory grade to start with is No. 80 grit.

Welding: Any of the conventional welding methods can be used. When filler rod is required, Low Expansion "42" is suggested.

Brazing: Copper and zinc-free brazing alloys are suggested.

Forging: The forging temperature should be 2150/2200° F (1177/1204° C). Avoid prolonged soaking to prevent sulfur absorption from the furnace atmosphere.

Annealing: Heat to 1450° F (788° C), and hold at heat for at least one-half hour per inch of thickness, air cool.

MECHANICAL PROPERTIES: as annealed

Tensile strength
ksi 75
MPa 517
Yield strength
ksi 40
MPa 276
Elongation in 2" (50.8 mm), % 30
Hardness, Rockwell B 76
Modulus of elasticity
psi x 10^6 .... 21.5
MPa x 10^3 .... 148.4

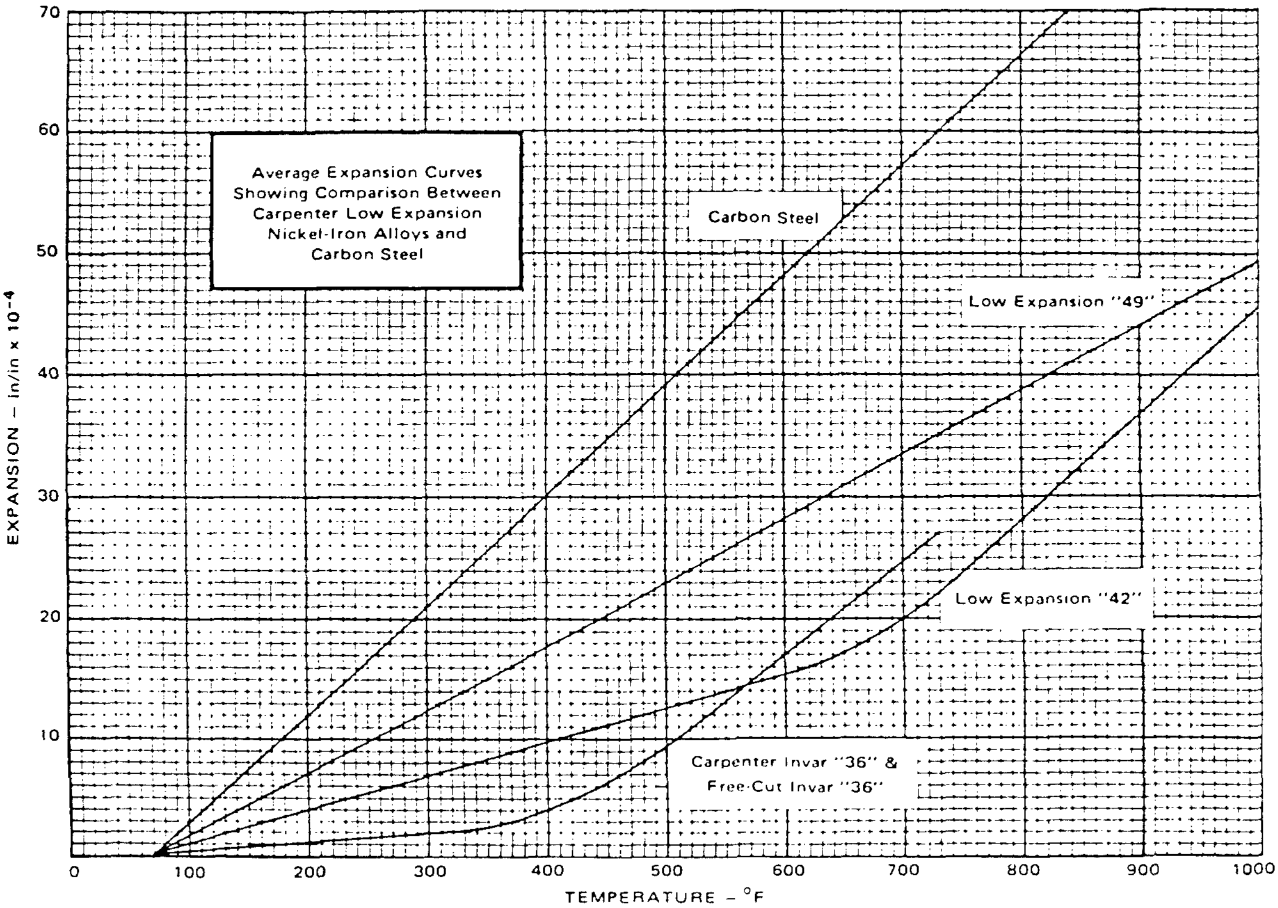
FORMS AVAILABLE:

Strip — Cold Rolled
Annealed
Annealed for Deep Drawing

Wire — Cold Drawn
Annealed

Bars — Hot Rolled
Cold Drawn
Centerless Ground
Annealed
Flats, Squares

11-80/8½M


Average Expansion Curves
Showing Comparison Between
Carpenter Low Expansion
Nickel-Iron Alloys and
Carbon Steel
Carbon Steel
Low Expansion "49"
Low Expansion "42"
Carpenter Invar "36" &
Free-Cut Invar "36"
EXPANSION – in/in x 10⁻⁴
TEMPERATURE – °F
0
10
20
30
40
50
60
70
100
200
300
400
500
600
700
800
900
1000

APPENDIX D

ALUMINUM PISTON DESIGN FOR ENGINE BUILD B/N-06

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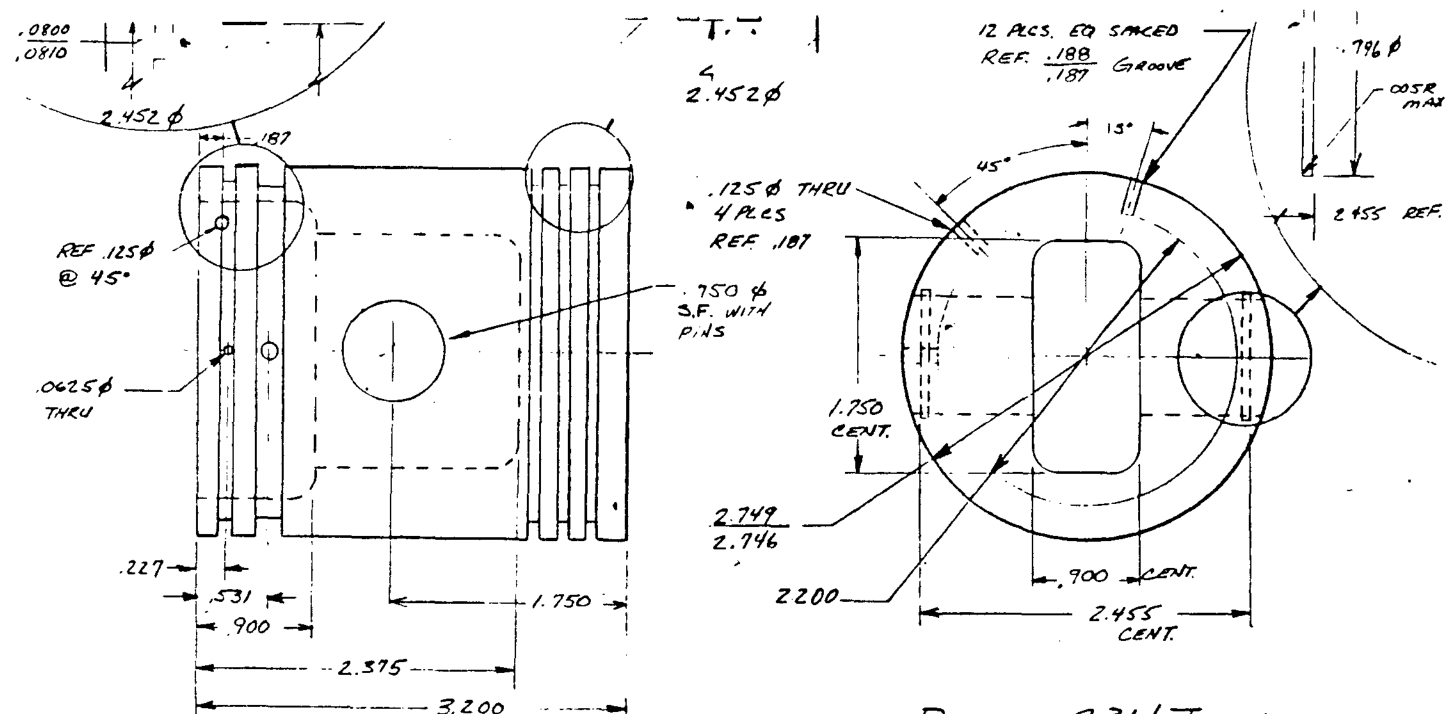

PISTON – 2 3/4ϕ TIMONEY

PROJ. 3407-02 FEB 20 1984

NOTE

1. ALL INSIDE RADII = .187
2. MAT'L : ALUMINUM
3. RING DIM BRIGGS + STRATTON # 277815

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APPENDIX E

COMPONENT PROFILE MEASUREMENTS
FOR ENGINE BUILD B/N-07

- Piston Dimensions and Profilometry Curves
- Cylinder Dimensions and Profilometry Curves

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EATON Engineering & Research Center

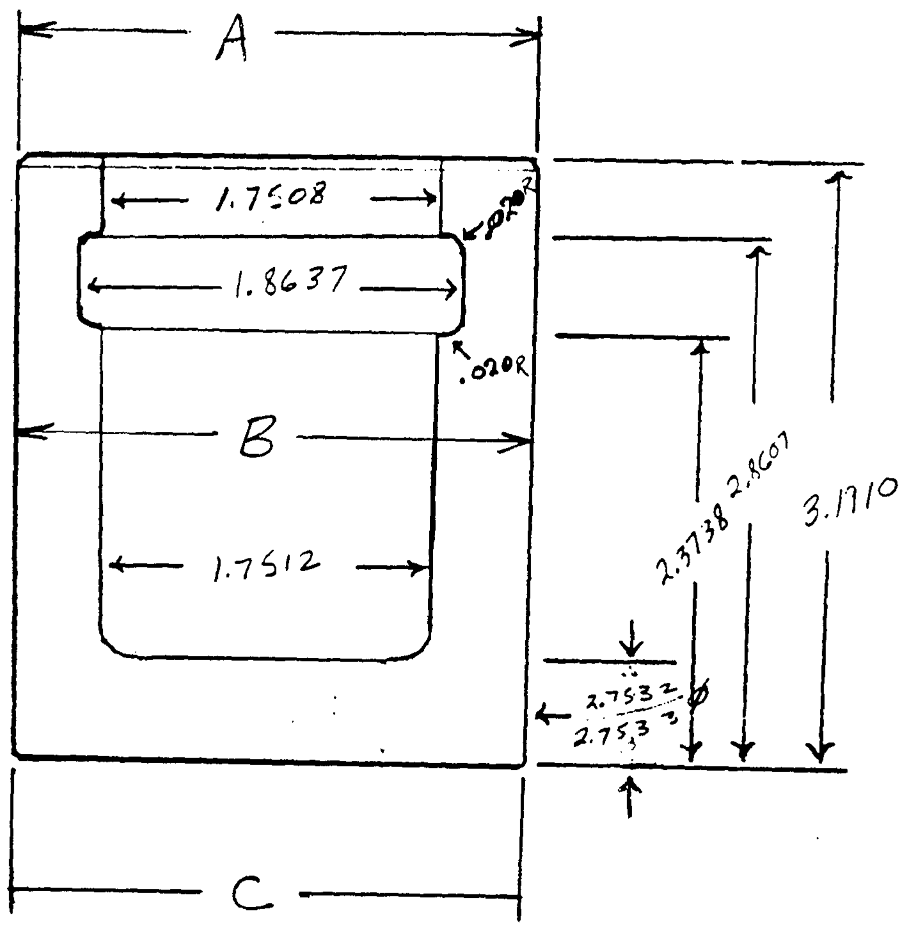
COMPONENT QUALITY RECORD

PART NO. F372   PROJECT NO. 3407-02

PART DESCRIPTION: PISTON P/N-02   S/N

INSPECTED BY: J. A. OLSON   DATE 4-2-84 original G.C.

INTENDED USE OF COMPONENT ASSEMBLY: 11-13-84 O.D. reground



DIMENSION:	A	B	C
	2.7396 / 2.7397	2.7397	2.7397

EATON Engineering & Research Center

COMPONENT QUALITY RECORD

PART NO. F372

PART DESCRIPTION: PISTON P/N-05

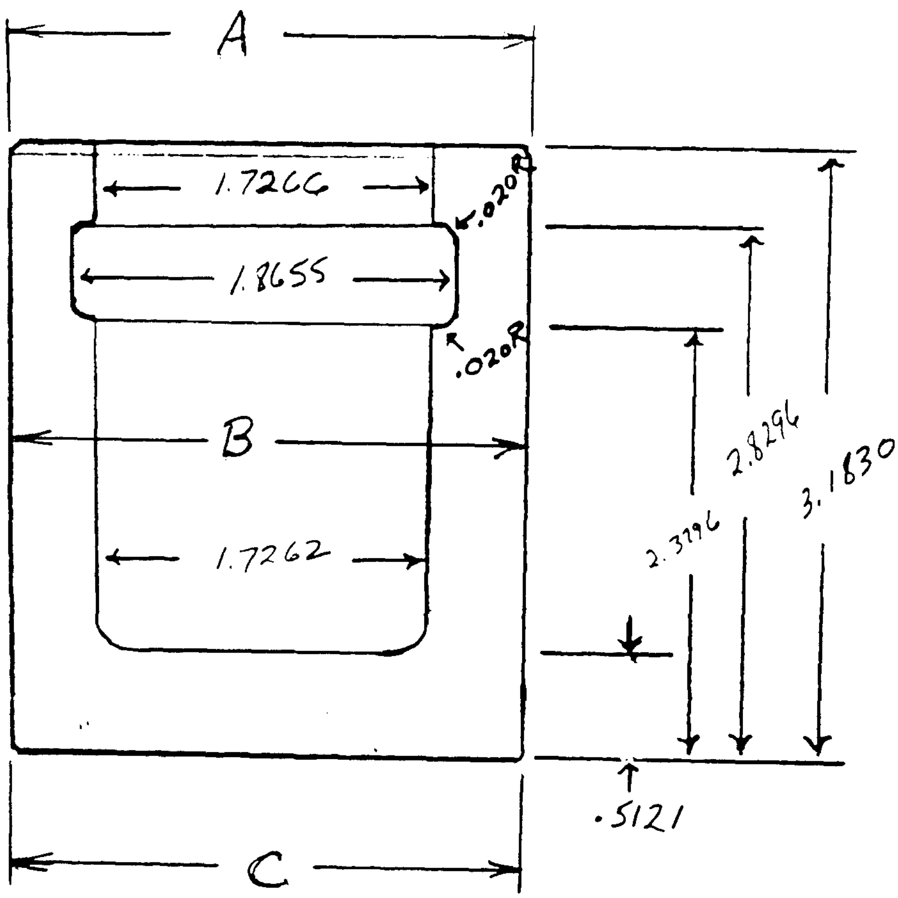
INSPECTED BY: J. A. OLSON

INTENDED USE OF COMPONENT ASSEMBLY:

PROJECT NO. 3407 – 02

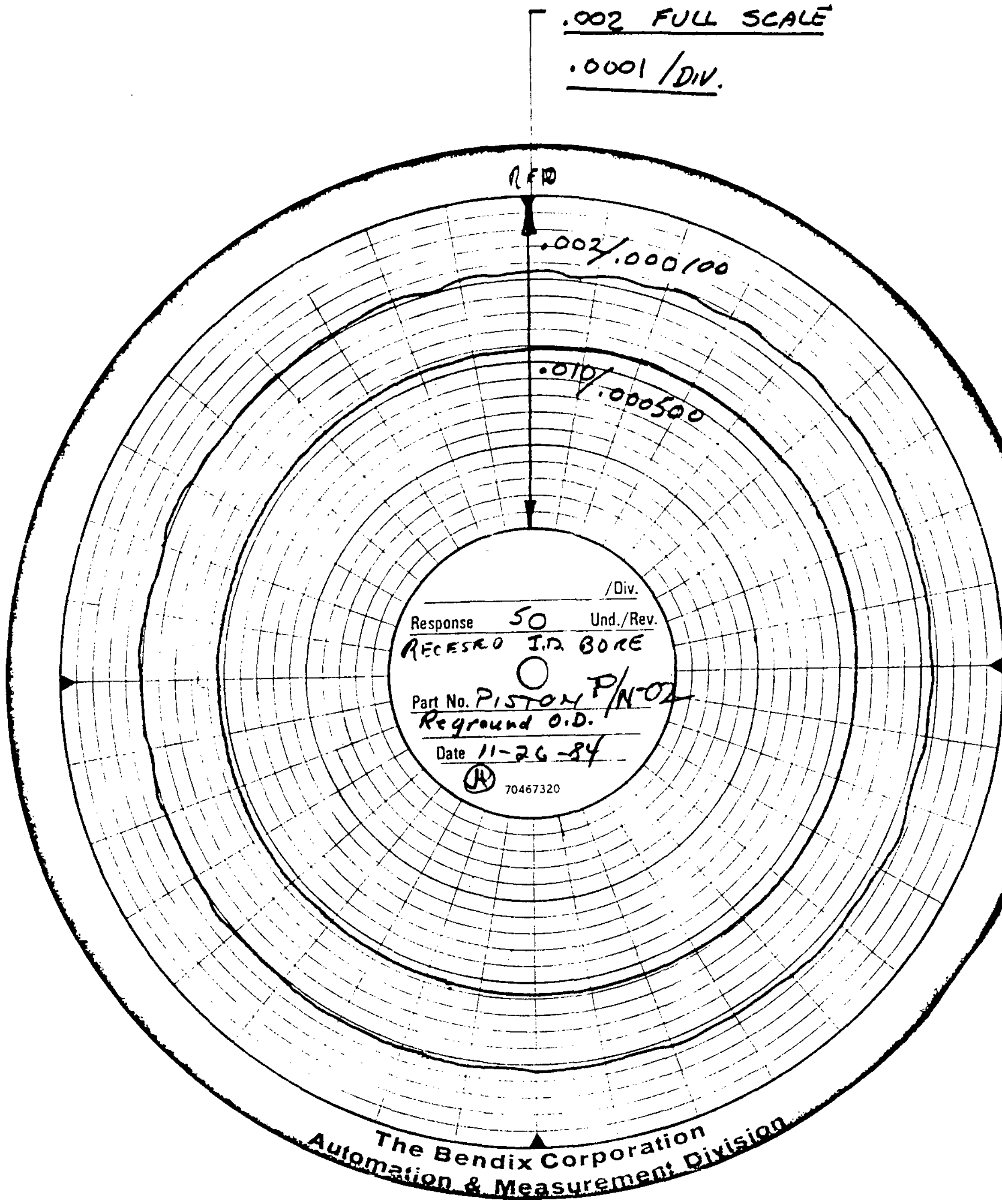
S/N

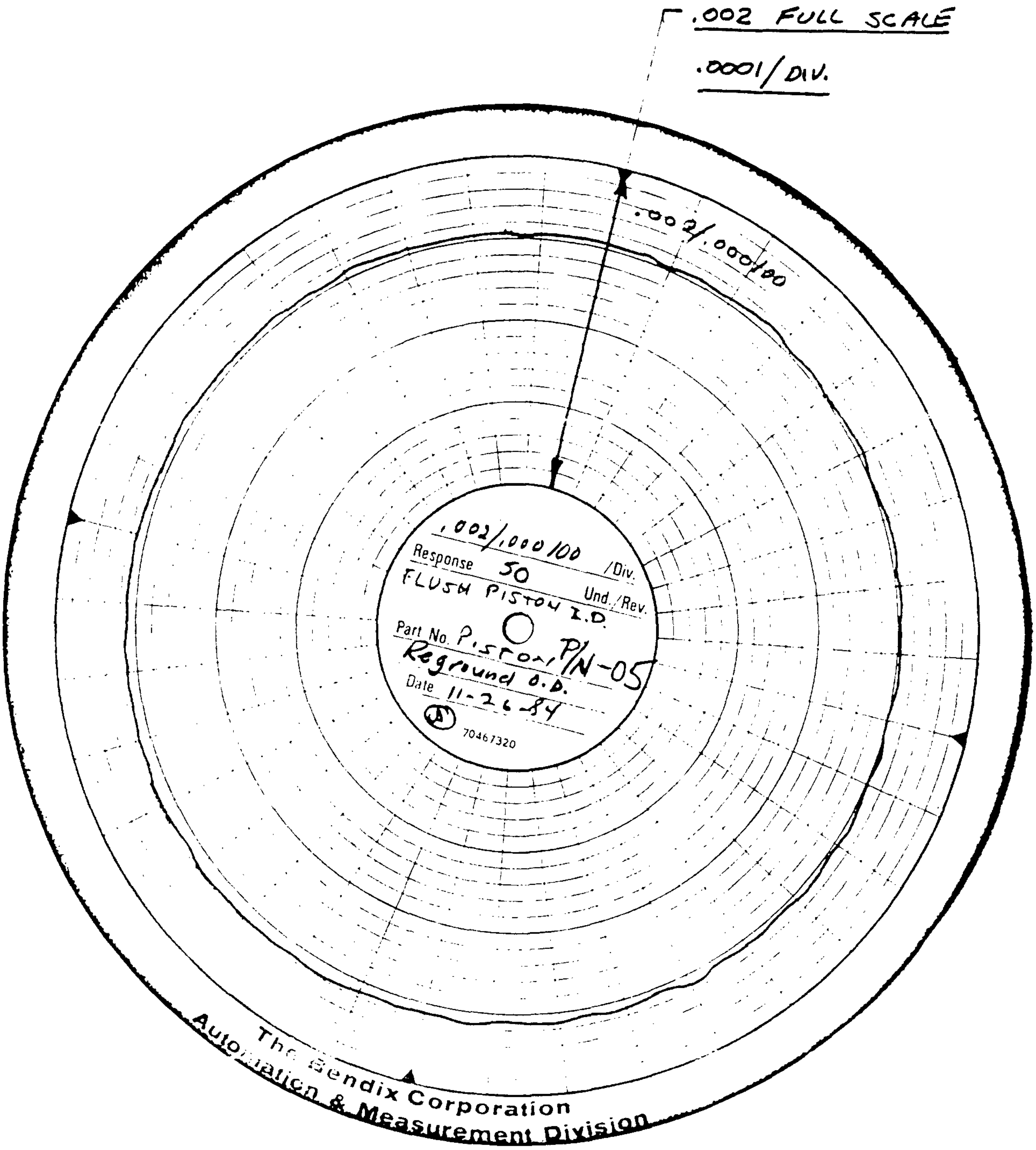
DATE 4-2-84 original Q.C.
11-13-84 O.D. measured



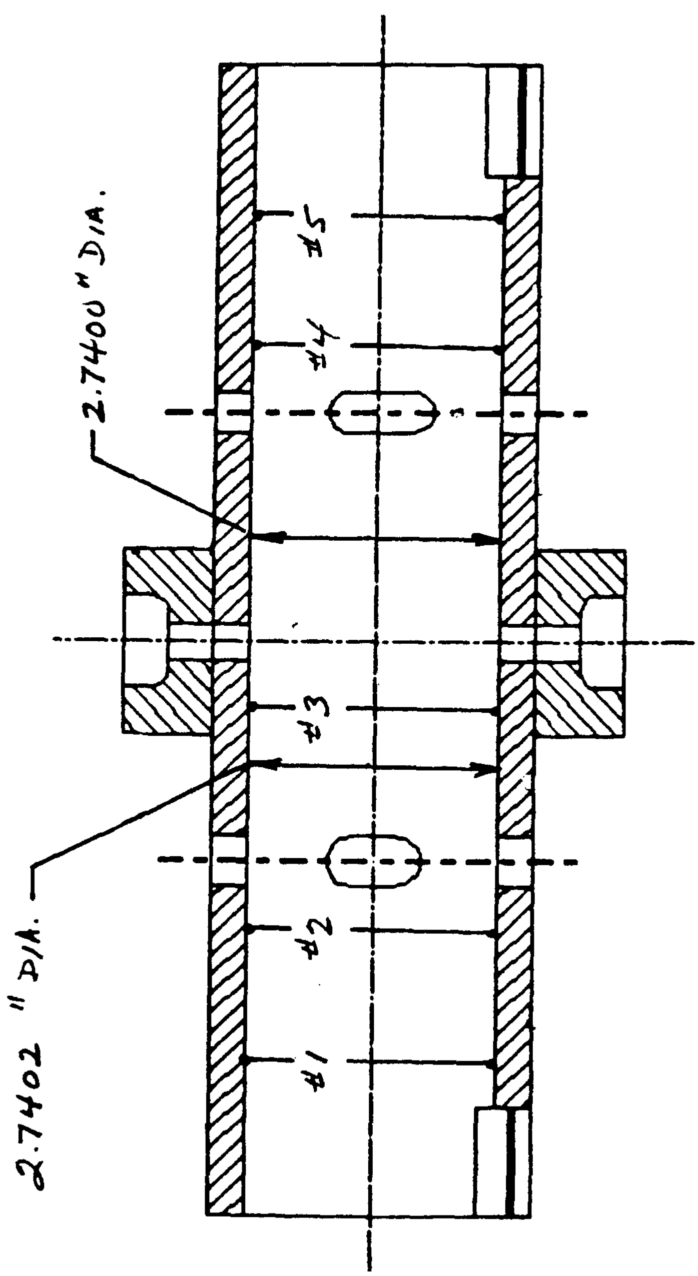
DIMENSION:

A	B	C
2.7397	2.7396	2.7396
2.7398	2.7397	

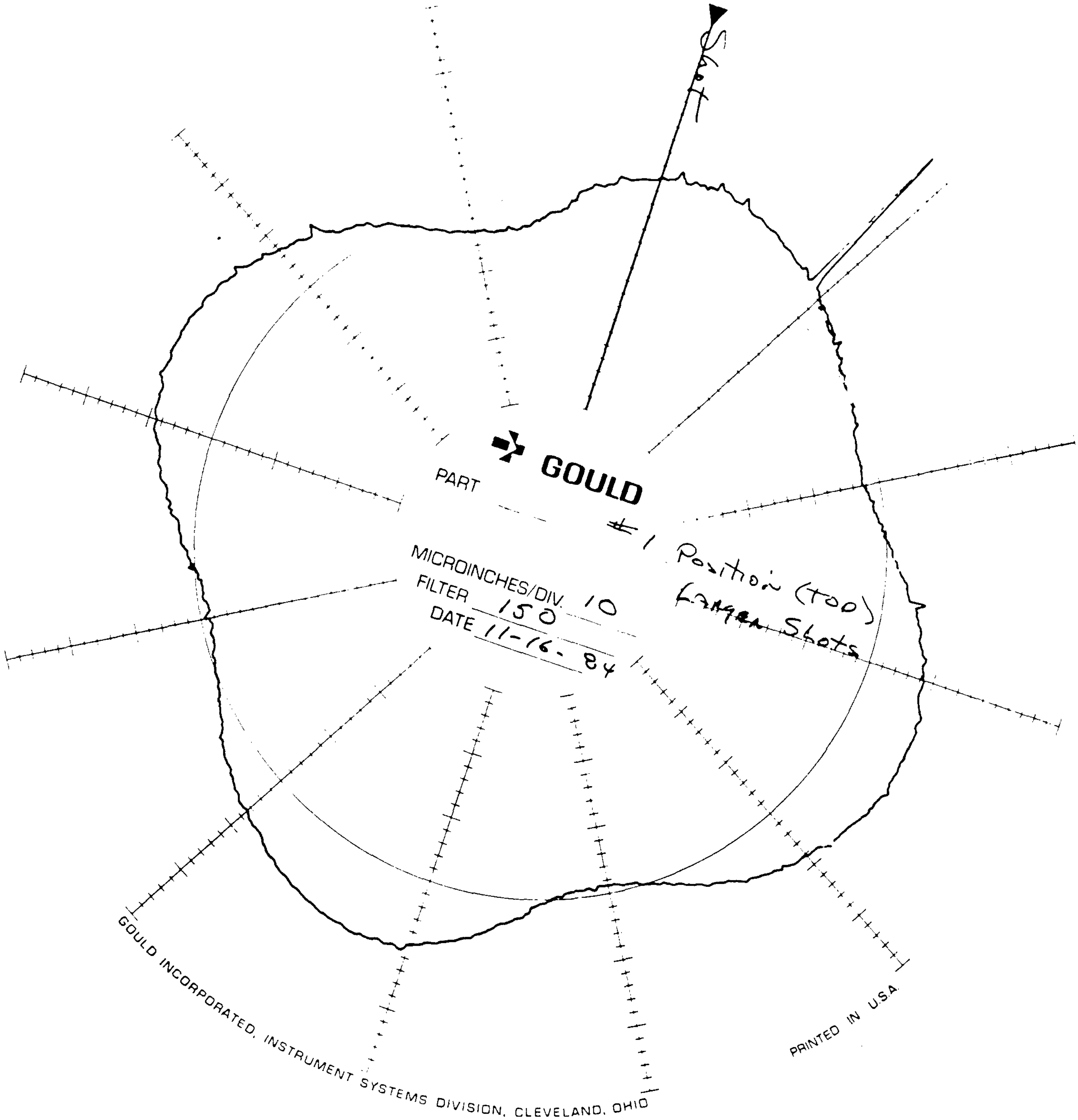

.002 FULL SCALE
.0001 /DIV.
REF
.002/.000100
.010/.000500
/Div.
Response 50 Und./Rev.
RECESSED I.D. BORE
Part No. PISTON P/N-02
Reground O.D.
Date 11-26-84
70467320
The Bendix Corporation
Automation & Measurement Division



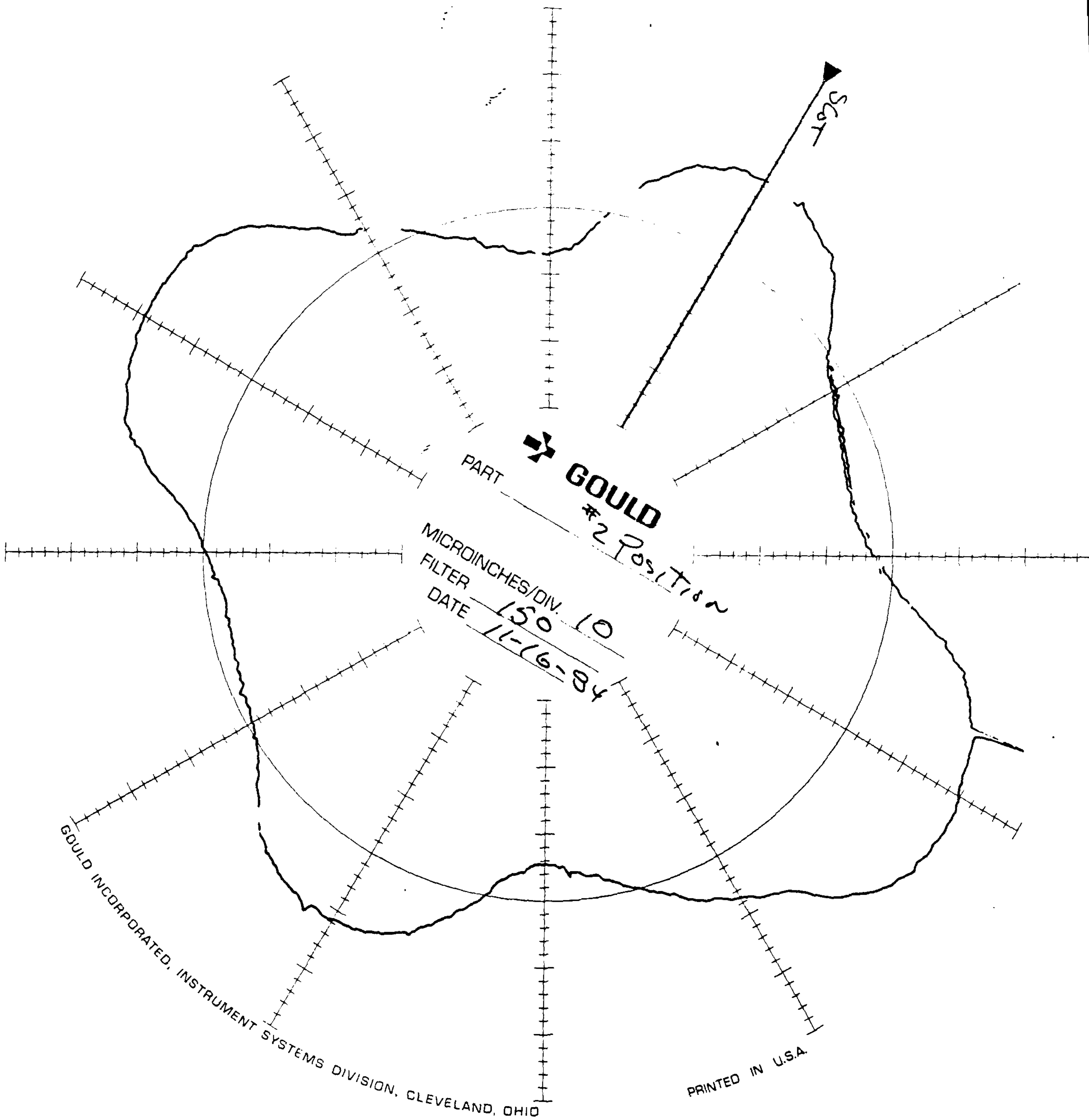
.002 FULL SCALE
.0001/DIV.
.002/.000100
.002/.000100 /Div.
Response 50 Und./Rev.
FLUSH PISTON I.D.
Part No. Piston P/N-05
Reground O.D.
Date 11-26-84
70467320
The Bendix Corporation
Automation & Measurement Division

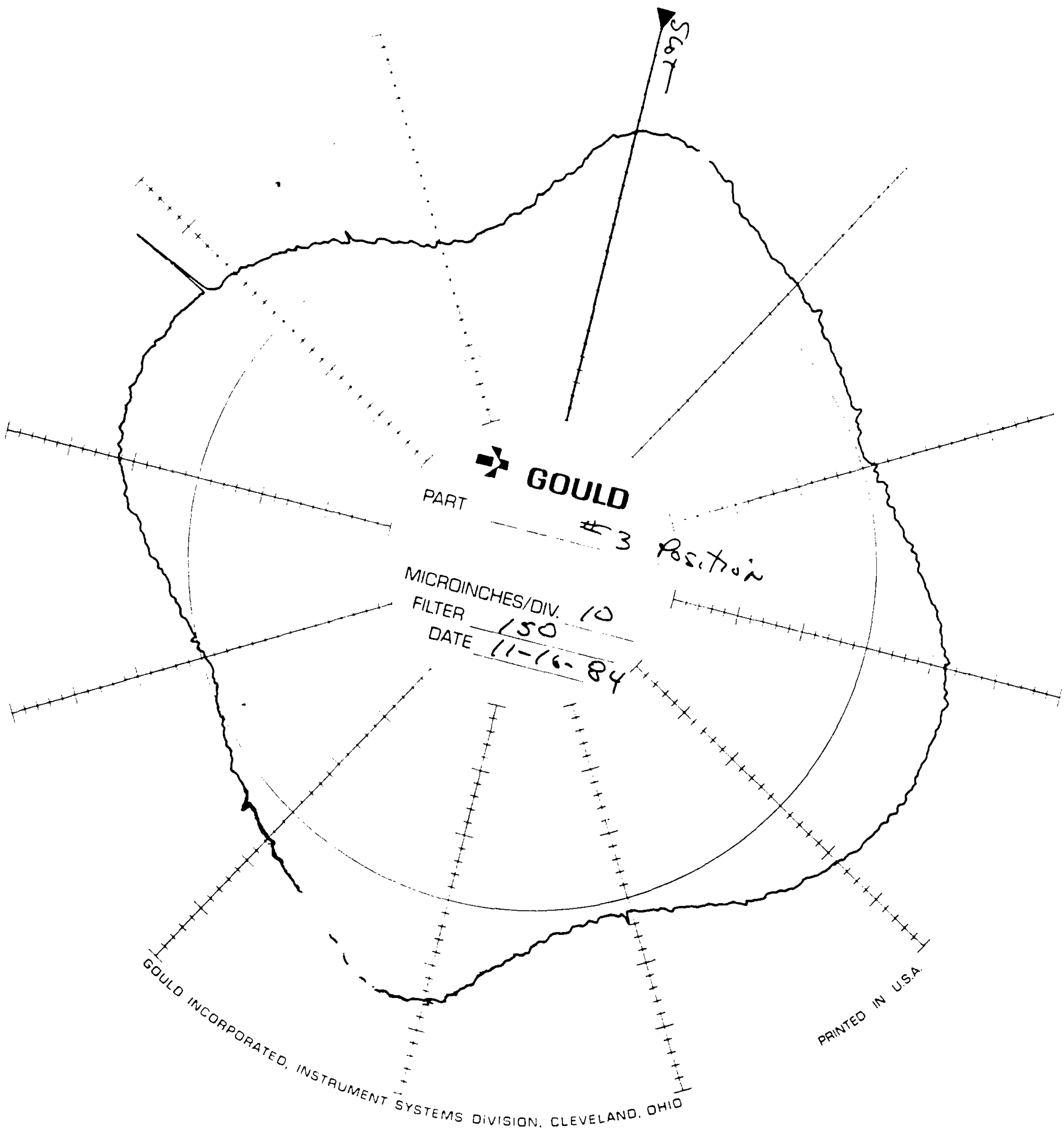


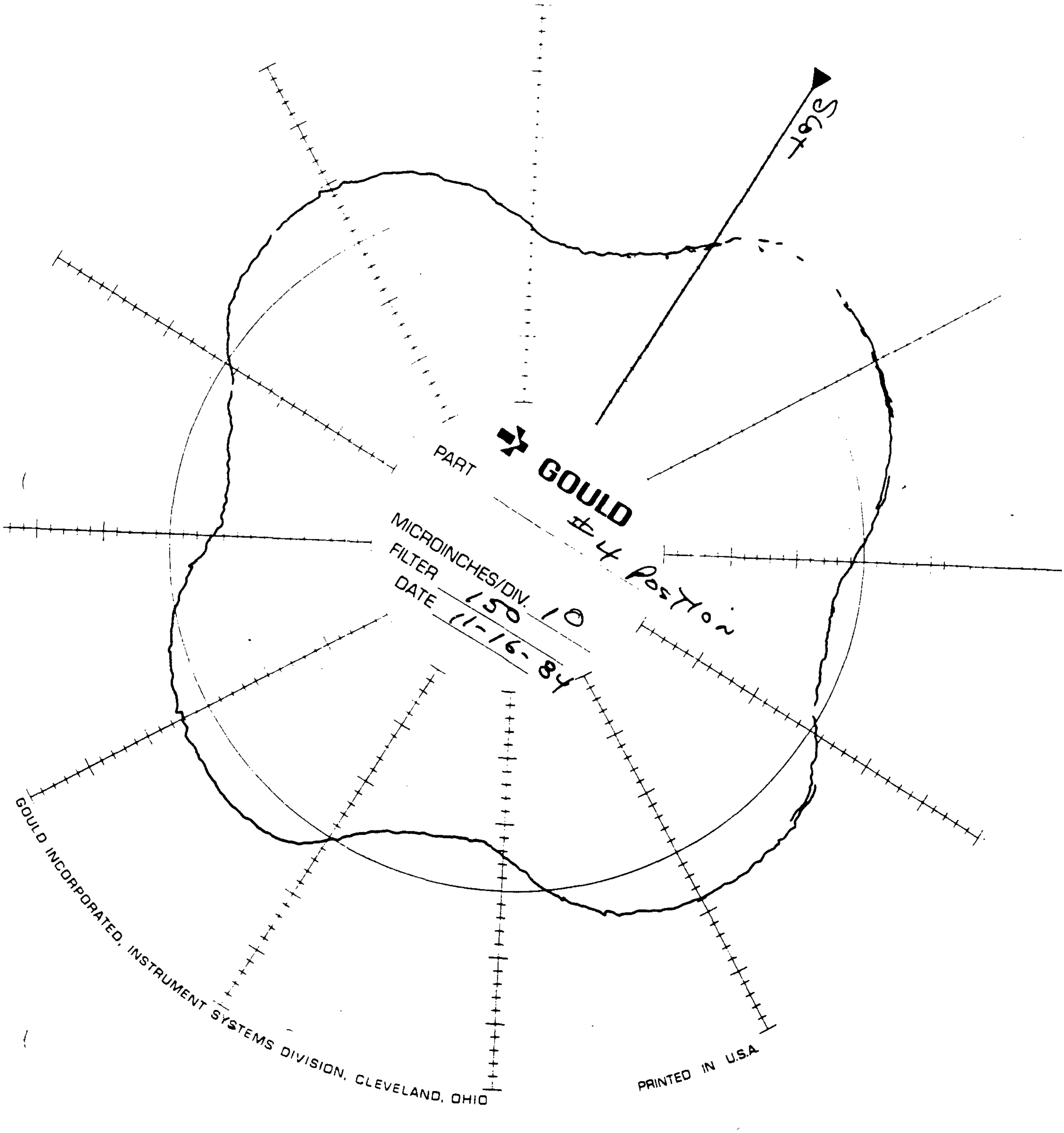
NOTE: Position numbers indicate location of profile measurements.



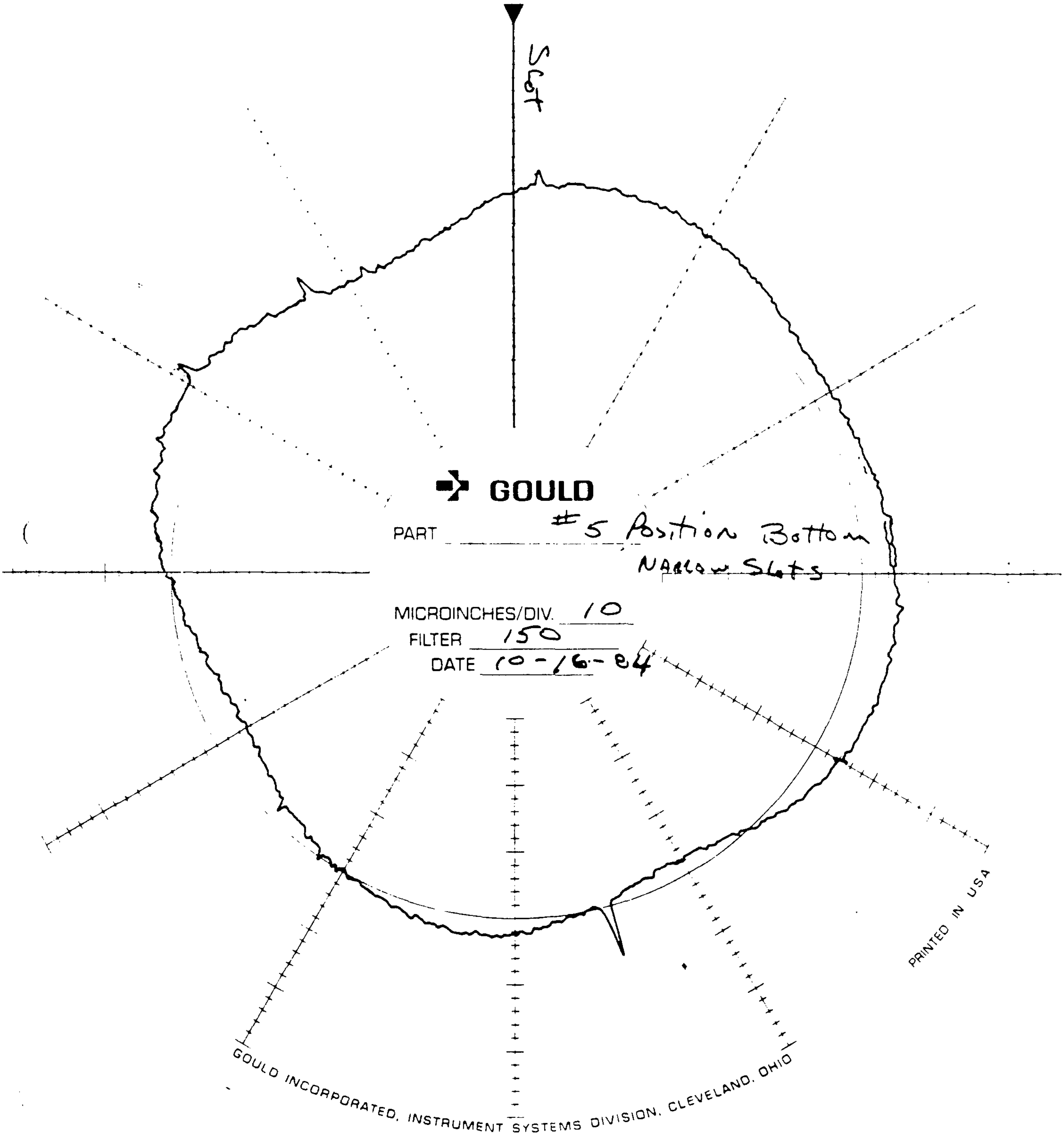
Shot
GOULD
PART #1 Position (top)
Larger Shots
MICROINCHES/DIV. 10
FILTER 150
DATE 11-16-84
GOULD INCORPORATED, INSTRUMENT SYSTEMS DIVISION, CLEVELAND, OHIO
PRINTED IN U.S.A.


GOULD
PART #2 Position
MICROINCHES/DIV. 10
FILTER 150
DATE 11-16-84
Slot
GOULD INCORPORATED, INSTRUMENT SYSTEMS DIVISION, CLEVELAND, OHIO
PRINTED IN U.S.A.


Slot
GOULD
PART #3 Position
MICROINCHES/DIV. 10
FILTER 150
DATE 11-16-84
GOULD INCORPORATED, INSTRUMENT SYSTEMS DIVISION, CLEVELAND, OHIO
PRINTED IN U.S.A.



Slot
GOULD
PART #4 Position
MICROINCHES/DIV. 10
FILTER 150
DATE 11-16-84
GOULD INCORPORATED, INSTRUMENT SYSTEMS DIVISION, CLEVELAND, OHIO
PRINTED IN U.S.A.


Slot
GOULD
PART #5 Position Bottom
Narrow Slots
MICROINCHES/DIV. 10
FILTER 150
DATE 10-16-84
PRINTED IN USA
GOULD INCORPORATED, INSTRUMENT SYSTEMS DIVISION, CLEVELAND, OHIO

APPENDIX F

COMPONENT PROFILE MEASUREMENTS FOR ENGINE BUILD B/N-08

- Piston Dimensions and Profilometry Curves
- Cylinder Dimensions and Profilometry Curves

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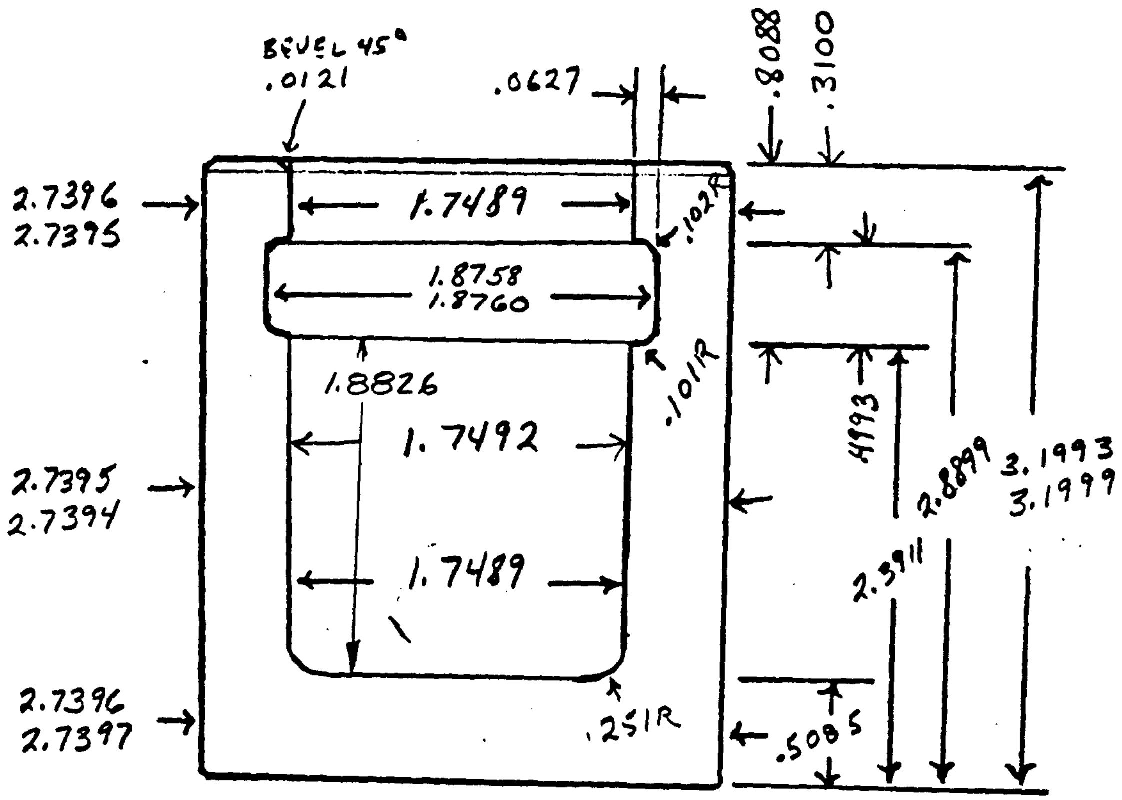
EATON Engineering & Research Center

COMPONENT QUALITY RECORD

PART NO. ____________________ PROJECT NO. 3407-02
PART DESCRIPTION: PISTON P/N-A S/N A
INSPECTED BY: J.A. OLSON DATE 2-12-85
INTENDED USE OF COMPONENT ASSEMBLY: ____________________



EATON

Eaton Corporation
Engineering & Research
Center

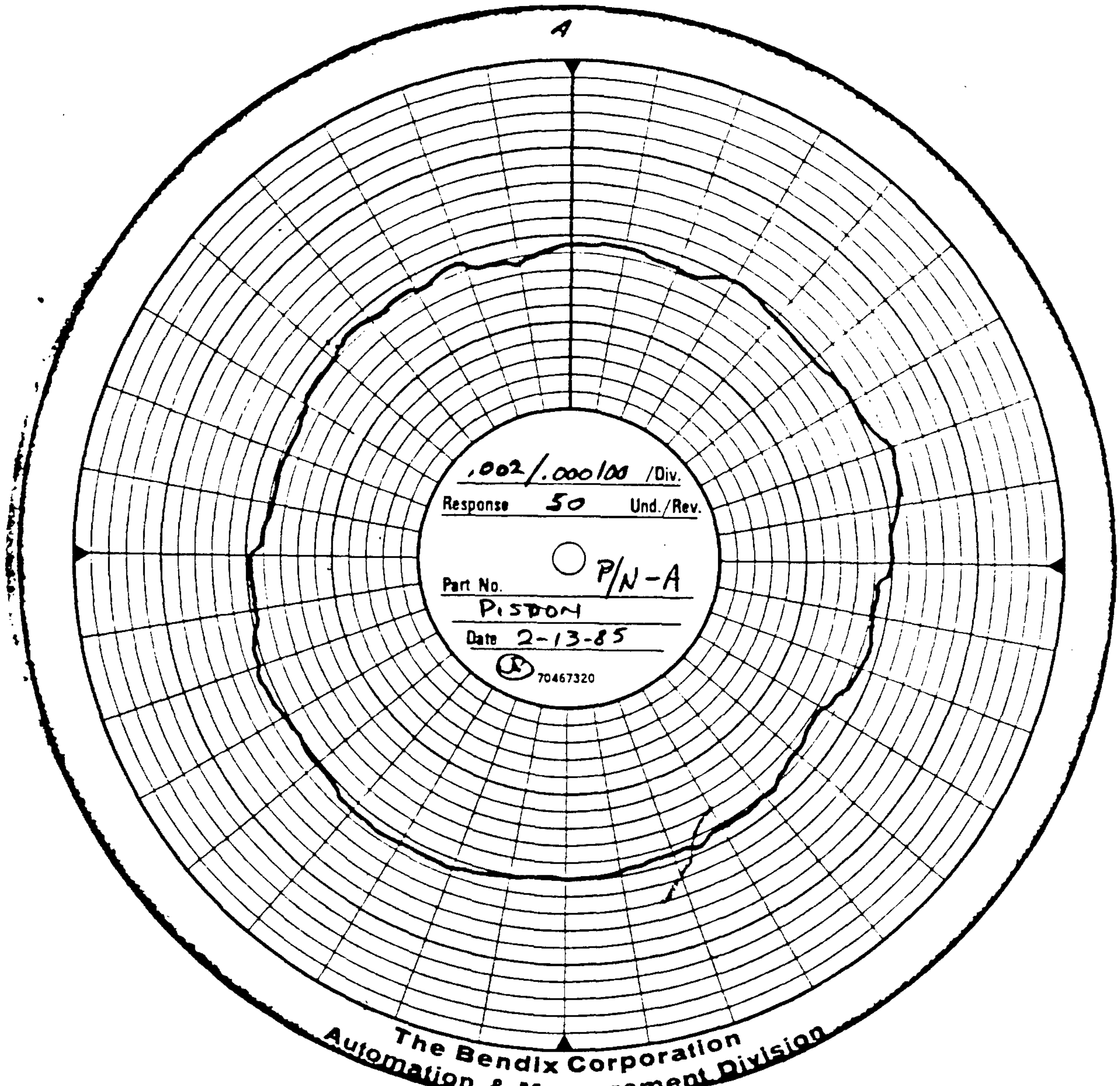
Component Quality Record

Part No. ______ Rev. ______ Project No. 3407-02 Date 2-13-85

Part Name PISTON P/N-A Lot ______ Qty. 1

Inspected By: J.A. OLSON P.O/W.O. ______

Assembly No. ______ Engineer ______



EATON Engineering & Research Center

COMPONENT QUALITY RECORD

PART NO.

PART DESCRIPTION: PISTON P/N-B

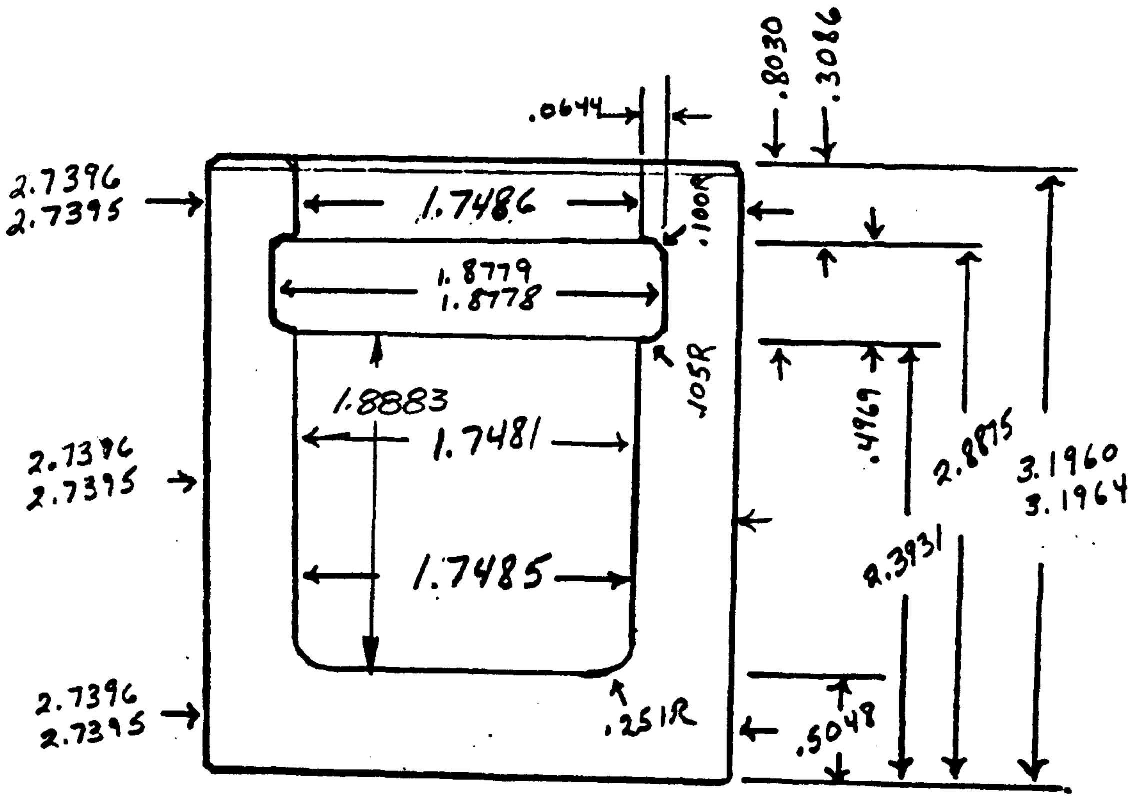
INSPECTED BY: J. A. OLSON

INTENDED USE OF COMPONENT ASSEMBLY:

PROJECT NO. 3407-02

S/N B

DATE 2-12-85

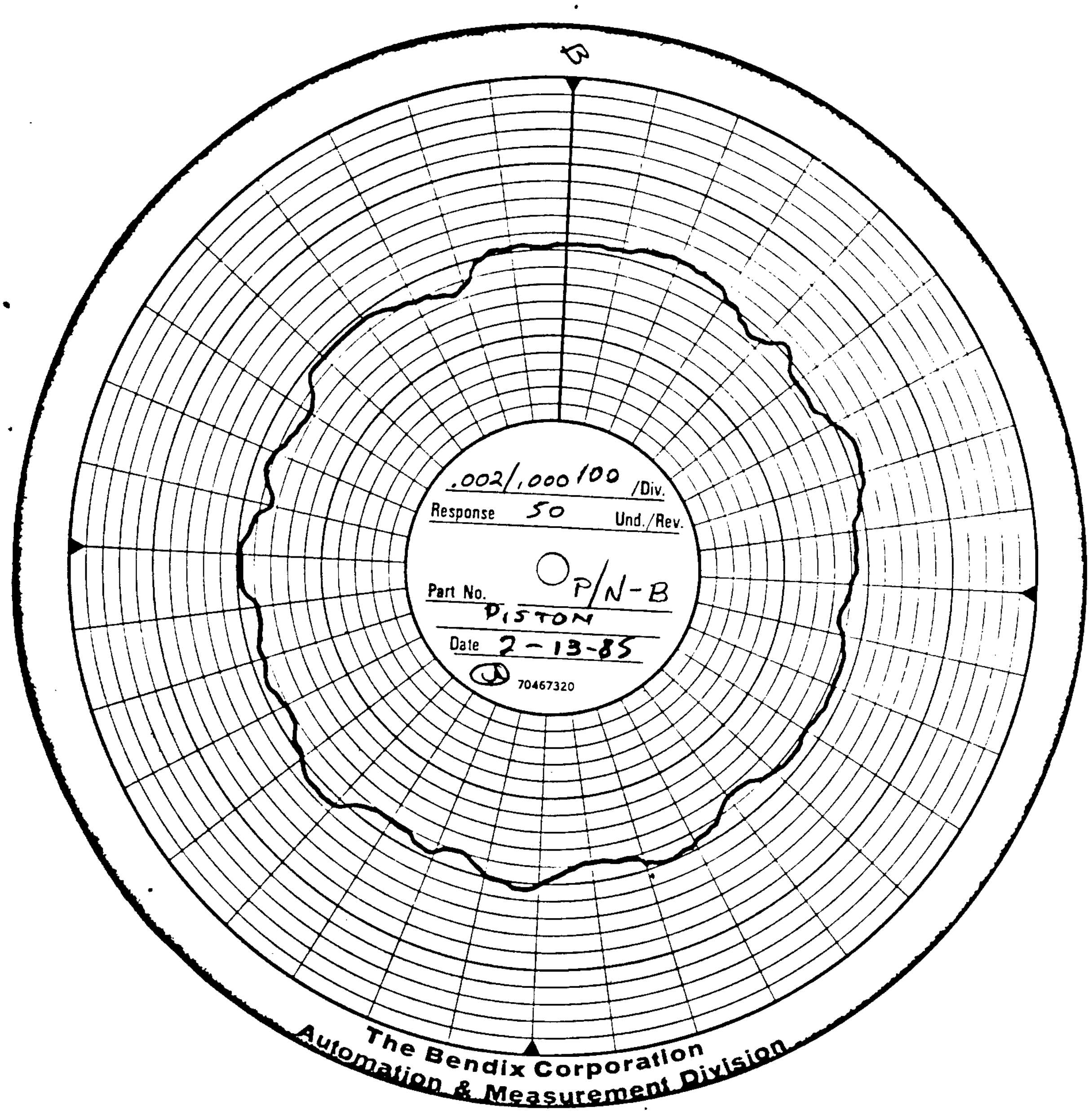


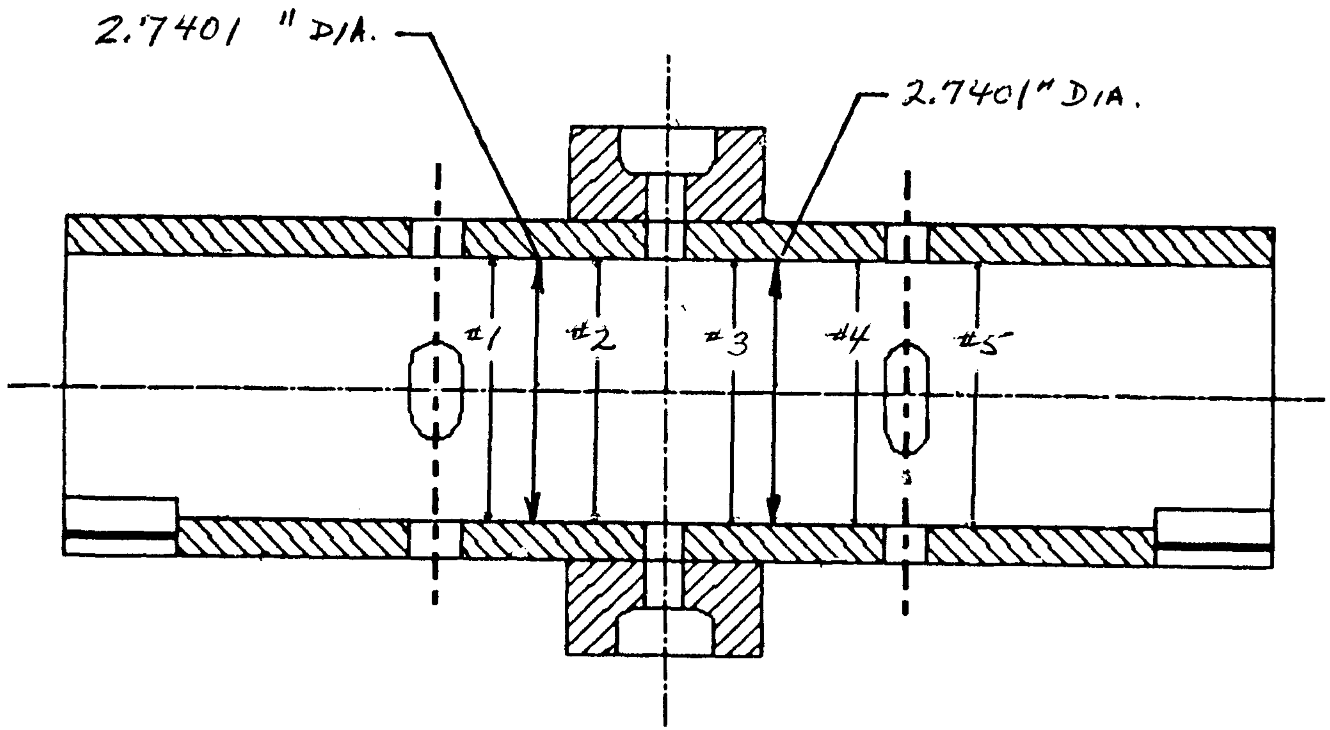
EATON

Eaton Corporation
Engineering & Research
Center

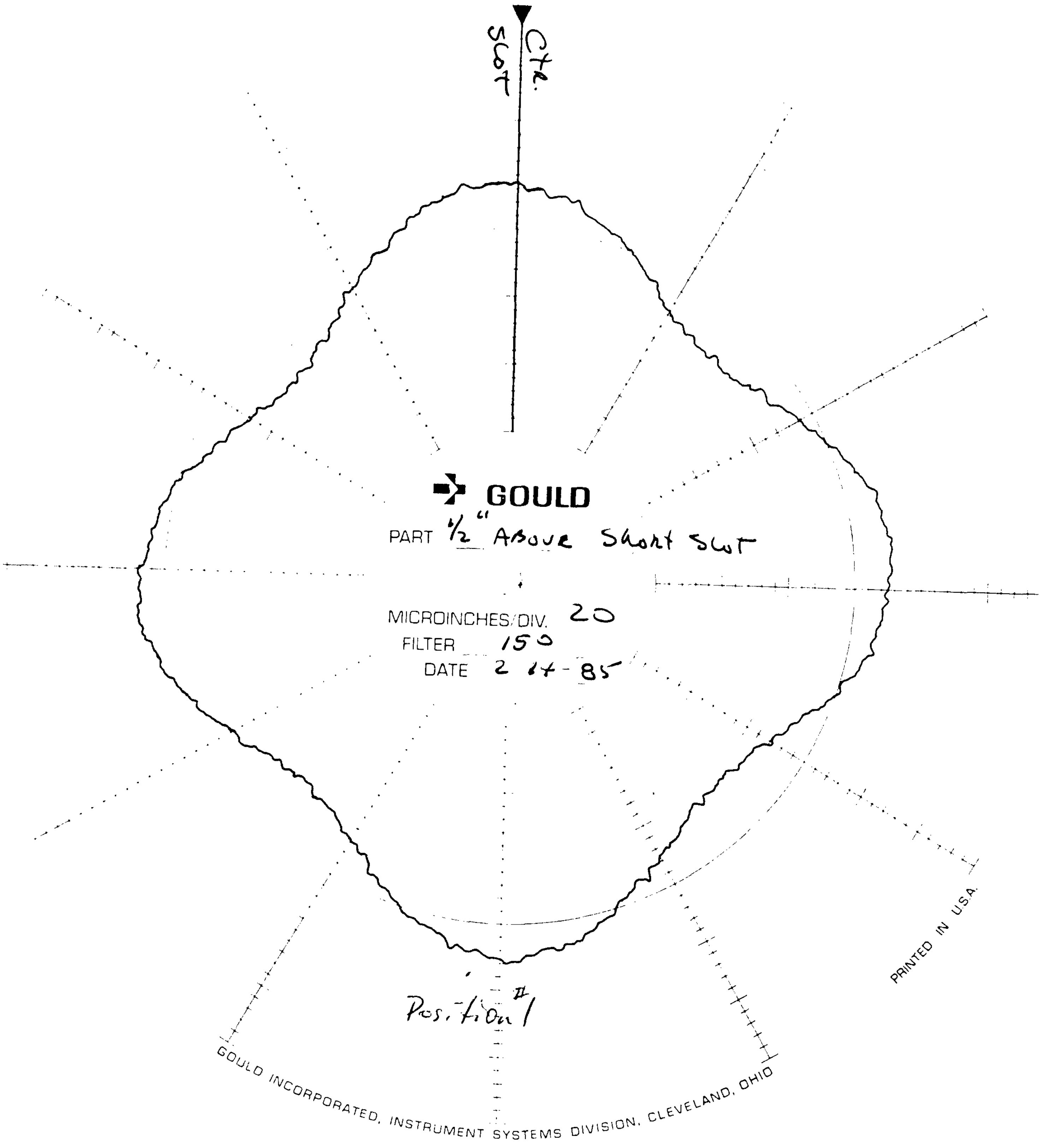
Component Quality Record

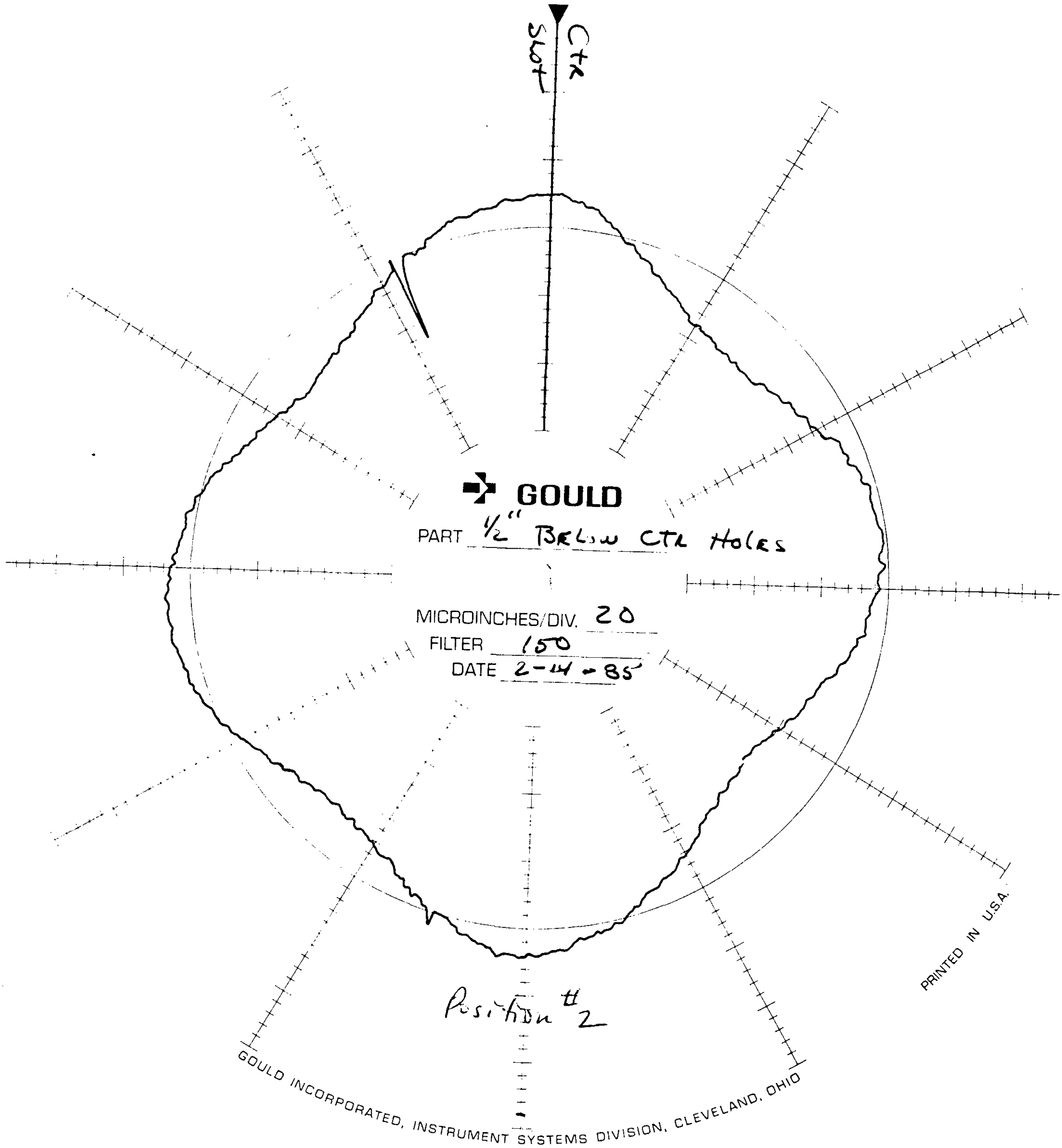
Part No. ________ Rev. ________ Project No. 3407-02 Date 2-13-85
Part Name PISTON P/N-B Lot ________ Qty. ________
Inspected By: V.A. OLSON P.O./W.O. ________
Assembly No. ________ Engineer ________

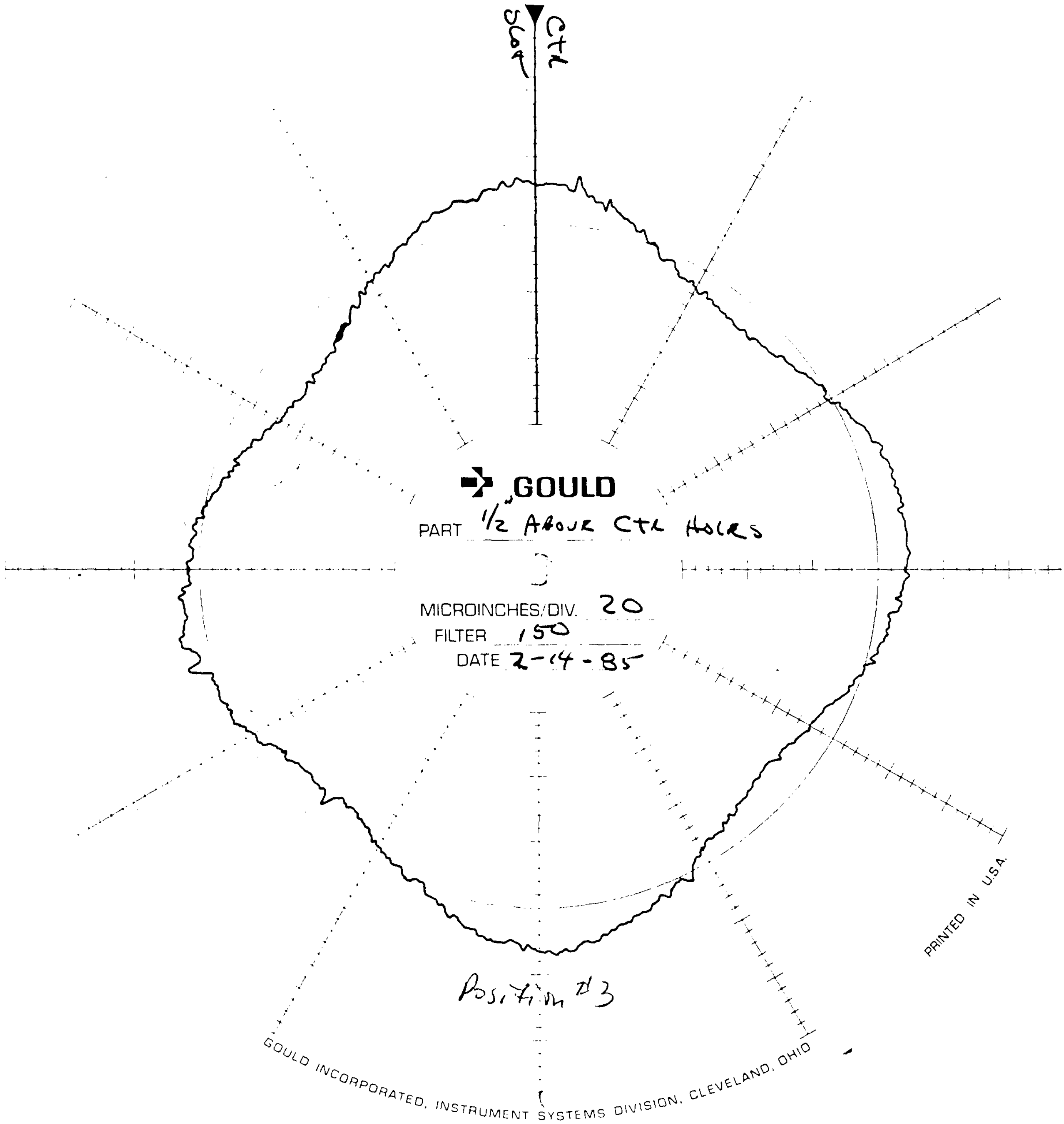


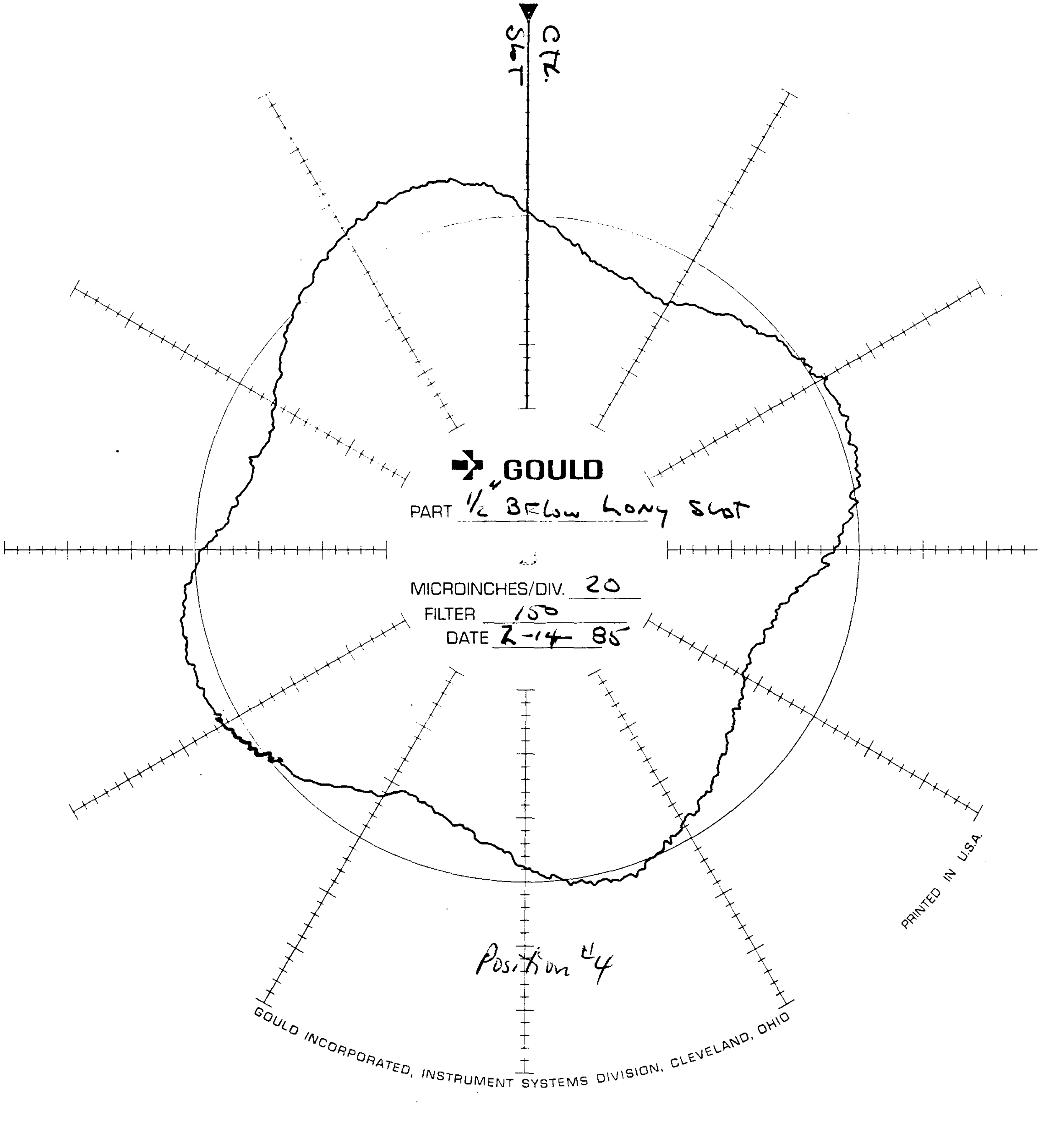


NOTE: Position numbers indicate location of profile measurements.

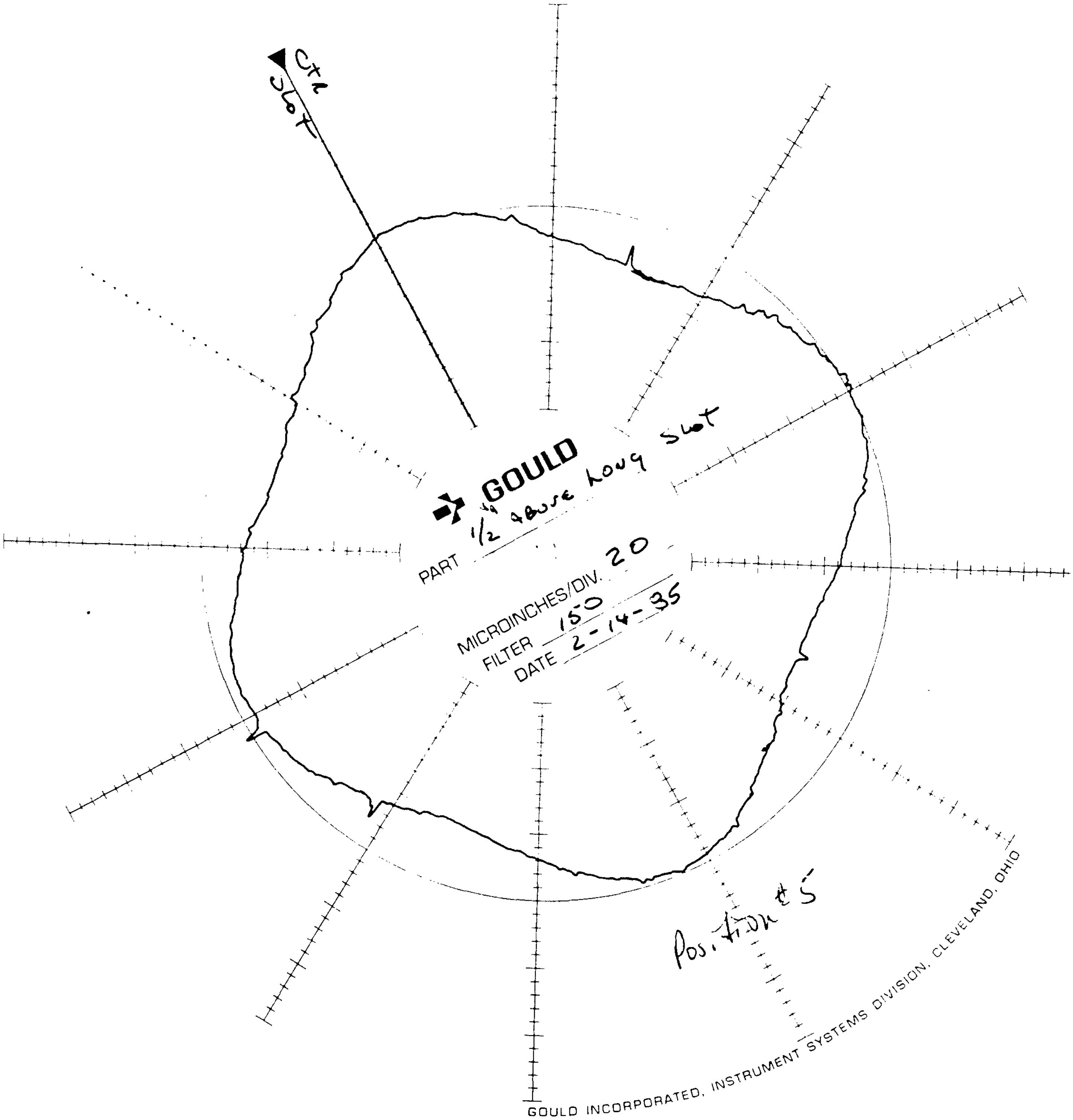

Ctr. Slot
GOULD
PART 1/2" Above Short Slot
MICROINCHES/DIV. 20
FILTER 150
DATE 2 14-85
Position #1
PRINTED IN U.S.A.
GOULD INCORPORATED, INSTRUMENT SYSTEMS DIVISION, CLEVELAND, OHIO


Ctr Slot
GOULD
PART 1/2" Below Ctr Holes
MICROINCHES/DIV. 20
FILTER 150
DATE 2-14-85
Position #2
PRINTED IN U.S.A.
GOULD INCORPORATED, INSTRUMENT SYSTEMS DIVISION, CLEVELAND, OHIO


Ctr Slot
GOULD
PART 1/2" Above Ctr Holes
MICROINCHES/DIV. 20
FILTER 150
DATE 2-14-85
Position #3
PRINTED IN U.S.A.
GOULD INCORPORATED, INSTRUMENT SYSTEMS DIVISION, CLEVELAND, OHIO



CTR. SLT
GOULD
PART 1/2" BELOW LONG SLOT
MICROINCHES/DIV. 20
FILTER 150
DATE 2-14-85
Position #4
PRINTED IN U.S.A.
GOULD INCORPORATED, INSTRUMENT SYSTEMS DIVISION, CLEVELAND, OHIO



Ctr slot
GOULD
PART 1/2 above long slot
MICROINCHES/DIV. 20
FILTER 150
DATE 2-14-35
Position 5
GOULD INCORPORATED, INSTRUMENT SYSTEMS DIVISION, CLEVELAND, OHIO

APPENDIX G

COMPONENT PROFILE MEASUREMENTS

FOR ENGINE BUILD B/N-09

- Piston Dimensions and Profilometry Curves

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Engineering & Research Center

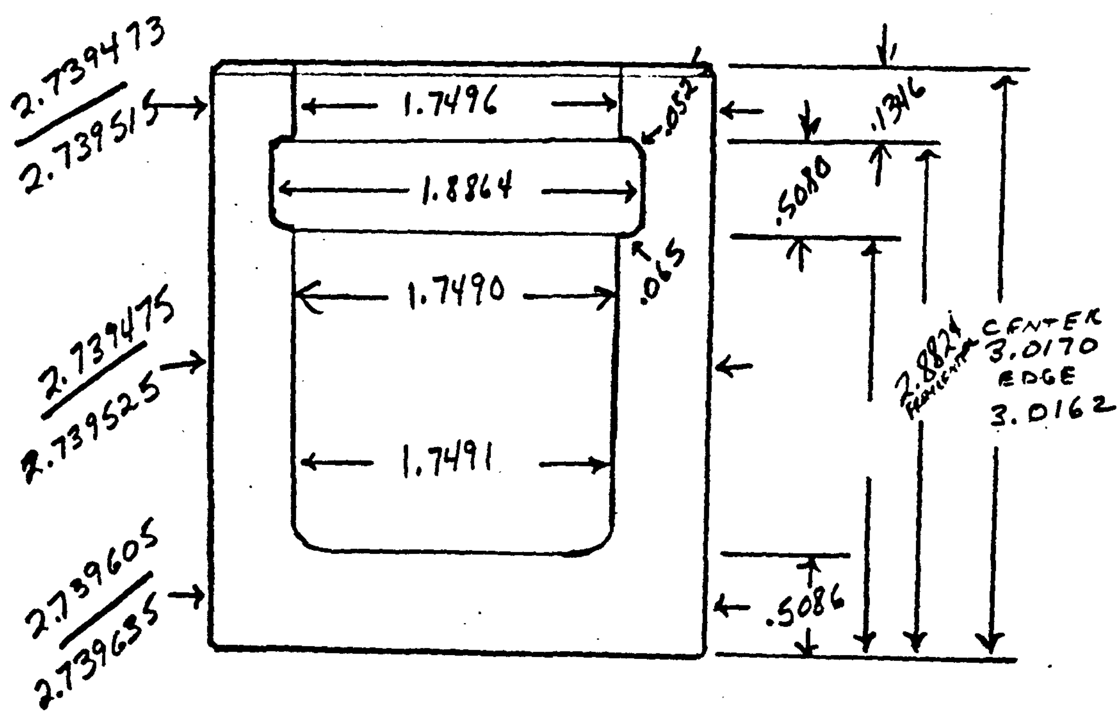
COMPONENT QUALITY RECORD

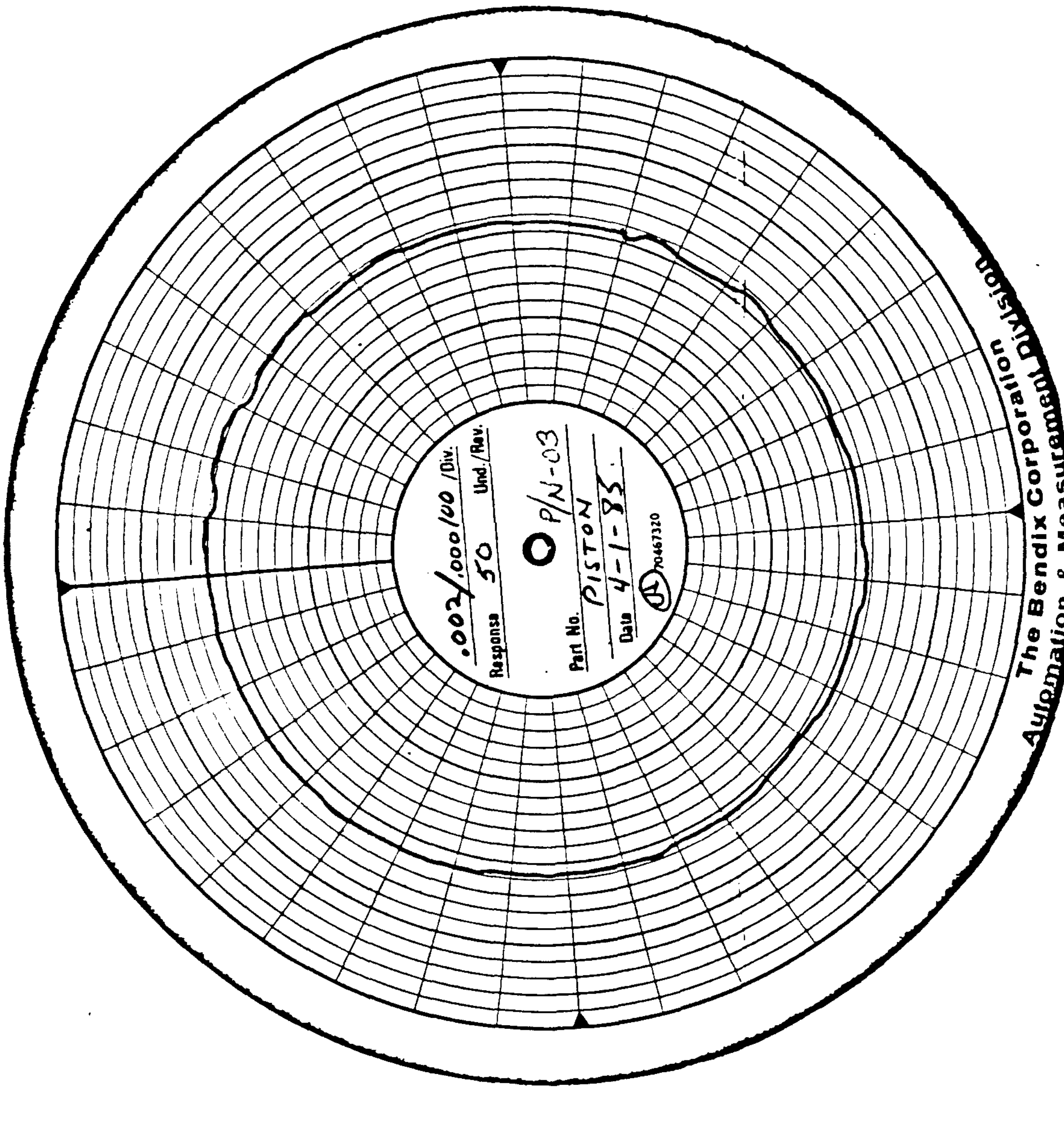
PART NO. ______________________ PROJECT NO. 3407-02

PART DESCRIPTION: PISTON P/N-03 S/N ______________________

INSPECTED BY: J.A. OLSON DATE 4-1-85

INTENDED USE OF COMPONENT ASSEMBLY: ______________________



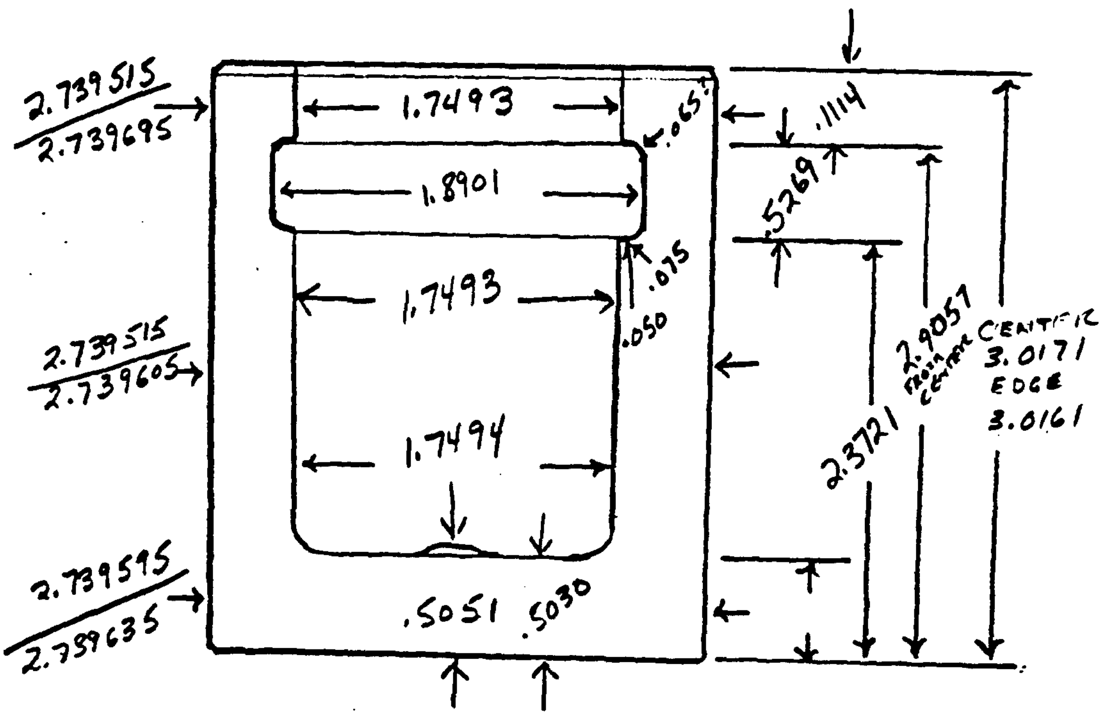

.002/.000100 /Div.
Response 50 Und./Rev.
Part No. PISTON P/N-03
Date 4-1-83
70467320
The Bendix Corporation
Automation & Measurement Division

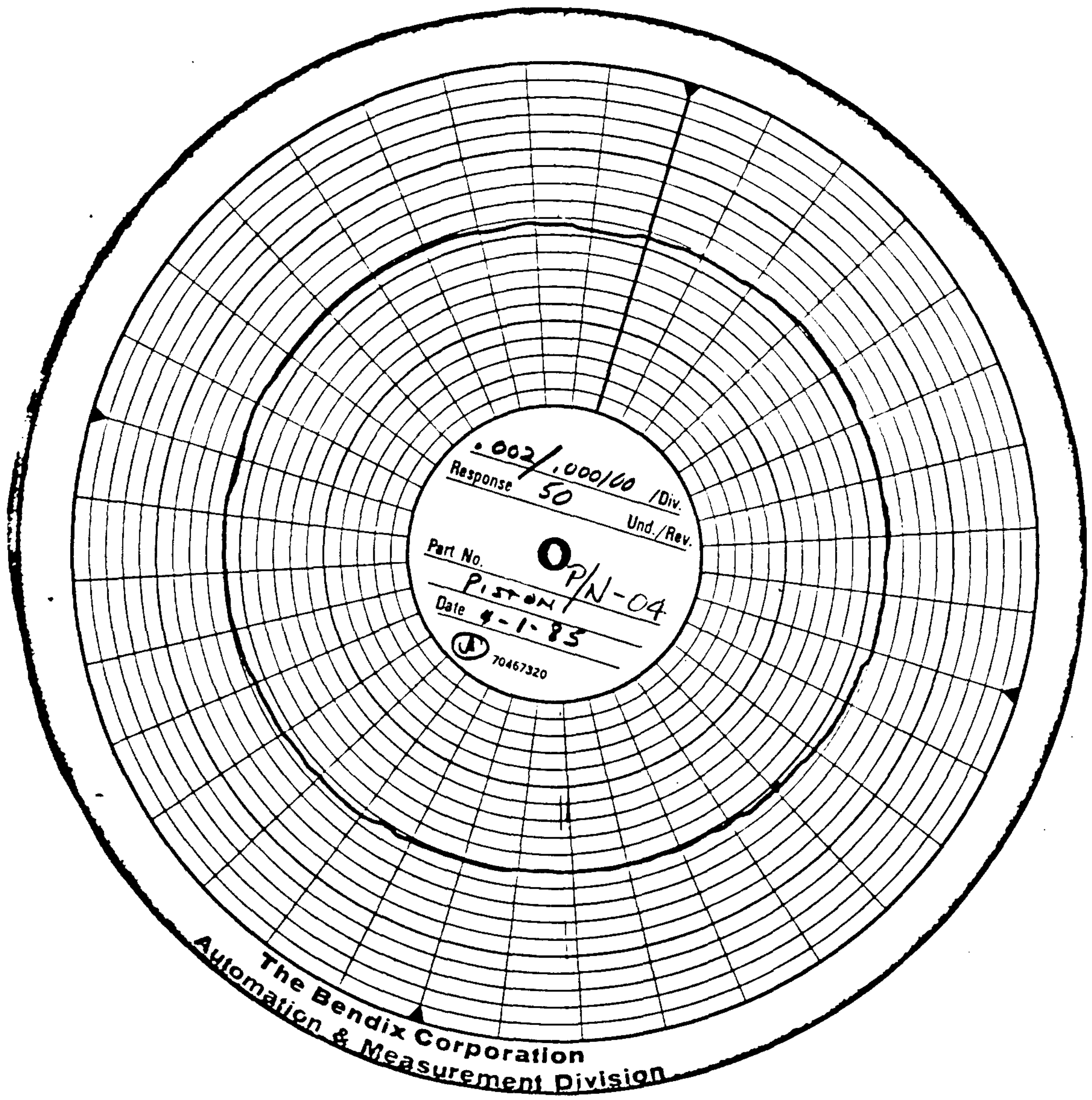
Engineering & Research Center

COMPONENT QUALITY RECORD

PART NO.
PART DESCRIPTION: PISTON P/N-04
INSPECTED BY: J.A OLSON
INTENDED USE OF COMPONENT ASSEMBLY:

PROJECT NO. 3407-02
S/N
DATE 4-1-85




.002/.000100 /Div.
Response 50 Und./Rev.
Part No. O P/N-04
Piston
Date 4-1-85
70467320
The Bendix Corporation
Automation & Measurement Division

APPENDIX H

MATERIAL CHARACTERIZATION REPORTS

- Sintered Alpha Silicon Carbide
- Partially Stabilized Zirconia
- Sialon

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JOB NO. : A85-1

CHARACTERIZATION REPORT

TO : W. P. BINNIE

DATE : 28-MAR-85

COPIES : J. ZANGHI
FILE

FROM : ROLAND CROSSLEY

SAMPLE DESIGNATION : SASIC MOR TEST BARS #,s 1-13(23C)
14-25(1200C)

MATERIAL DESCRIPTION : SINTERED ALPHA SiC LOT # 8414

NOTEBOOK REFS -- MAT'L :

DATA : F444-97

RESULTS SUMMARY :
(COPIES OF NOTEBOOK DATA ATTACHED)

STRENGTH DATA:

SAMPLE	TEMP.	NO. OF SPEC	AVG KSI	STD. DEV. KSI	AVG. MPa	STD. DEV. MPa	DENSITY
1-13	23C	13	51.85	8.25	357.53	56.87	3.14
14-25	1200C	12	55.00	4.13	379.22	28.45	

NAME: STEVE LACKI/RC DATE: 14-FEB-85

REF: BOOK-PAGE F444-97

PROJECT: SRX TITLE: STRENGTH MONITORING

JOB NUMBER A85-1 DATA SHEET NO. C-85-1-1

MATERIAL: SiC LOT #8414

TEST MODE 4-PT. FLEX TEST OUTER SPAN (IN) : 1.50
INNER SPAN (IN) : 0.75

CROSS HEAD SPEED 0.02 IN./MIN.
CHART SPEED 150 CM./HR. TEST TEMPERATURE: 23C
TEST DATE 13-FEB-85

SAMPLE NO.	WIDTH (IN.)	THICK (IN.)	PEAK LOAD (LBS.)	STRENGTH Ksi	STRENGTH MPa.	DENSITY GMS./CC
1	0.2500	0.1261	205.0	58.01	400.0	
2	0.2502	0.1264	127.0	35.74	246.4	
3	0.2508	0.1256	195.0	55.45	382.3	
4	0.2496	0.1264	183.0	51.63	356.0	
5	0.2503	0.1261	148.0	41.83	288.4	
6	0.2493	0.1262	217.0	61.49	423.9	
7	0.2523	0.1258	133.0	37.47	258.4	
8	0.2495	0.1258	207.0	58.98	406.7	
9	0.2480	0.1255	177.0	50.98	351.5	
10	0.2486	0.1258	187.0	53.47	368.7	
11	0.2502	0.1260	218.0	61.74	425.7	
12	0.2508	0.1264	201.0	56.43	389.1	
13	0.2495	0.1263	180.0	50.88	350.8	
			AVG.	51.85	357.53	
			STD. DEV.	8.25	56.87	

NAME: STEVE LACKI/RC DATE: 28-MAR-85

REF: BOOK-PAGE F444-97

PROJECT: SRX TITLE: STRENGTH MONITORING

JOB NUMBER A85-1 DATA SHEET NO. C-85-1-2

MATERIAL: SiC LOT #8414

TEST MODE 4-PT. FLEX TEST OUTER SPAN (IN) : 1.50
INNER SPAN (IN) : 0.75

CROSS HEAD SPEED 0.02 IN./MIN.
CHART SPEED 150 CM./HR. TEST TEMPERATURE: 1200C
TEST DATE 25-MAR-85

SAMPLE NO.	WIDTH (IN.)	THICK (IN.)	PEAK LOAD (LBS.)	STRENGTH Ksi	STRENGTH MPa.	DENSITY GMS./CC
14	0.2490	0.1259	187.0	53.30	367.5	
15	0.2498	0.1264	189.0	53.28	367.3	
16	0.2483	0.1259	191.0	54.60	376.4	
17	0.2524	0.1252	204.0	58.01	400.0	
18	0.2497	0.1260	164.0	46.54	320.9	
19	0.2491	0.1260	188.0	53.48	368.7	
20	0.2522	0.1262	208.0	58.26	401.7	
21	0.2525	0.1261	193.0	54.08	372.9	
22	0.2505	0.1254	208.0	59.40	409.6	
23	0.2493	0.1252	181.0	52.11	359.3	
24	0.2512	0.1259	225.0	63.57	438.3	
25	0.2492	0.1261	188.0	53.37	368.0	
			AVG.	55.00	379.22	
			STD. DEV.	4.13	28.45	

JOB NO. :A84-176

CHARACTERIZATION REPORT

TO : S. G. SESHADRI

FROM : THOMAS YOUNG

DATE : 20-Aug-84

COPIES : M. SRINIVASAN
FILE

SAMPLE DESIGNATION : MOR BARS NOS. 1 - 15

MATERIAL DESCRIPTION : NILSEN PSZ MAT'L., GRADE MS, MOR BARS

NOTEBOOK REFS -- MAT'L : DATA : F444-28

RESULTS SUMMARY :
(COPIES OF NOTEBOOK DATA ATTACHED)

BULK DENSITY RANGE: 5.719 GMS./CC TO 5.741 GMS./CC

SONIC MODULUS RANGE: SONIC E

30.06 Mpsi 207.2 GPa

TO

30.53 Mpsi 210.5 GPa

STRENGTH DATA:

TEMP: 500 C

NO. OF SPECIMENS TESTED: 15

AVG. STRENGTH: 66.17 KSI 456.2 MPa

STD. DEVIATION: 9.77 KSI 67.4 MPa

WEIBULL MODULUS= 5.21
SIGMA THETA= 72.03
CORR. COEF.= 0.89

RESEARCH LABORATORY NOTES THE CARBORUNDUM CO

NAME: THOMAS YOUNG DATE: 20-Aug-84

REF: BOOK-PAGE F444-28

PROJECT: MEF TITLE: OXIDE BASED SYSTEMS

DATA SHEET NO. C-84-176-1

JOB NUMBER A84-176

MATERIAL: NILSEN PSZ MAT'L., GRADE MS MOR BARS

TEST MODE 4-PT. FLEX TEST OUTER SPAN (IN) : 1.50
INNER SPAN (IN) : 0.75

CROSS HEAD SPEED 0.02 IN./MIN.
CHART SPEED 150 CM./HR. ** 500 C TEST TEMP. **
TEST DATE 20-AUG-84

SAMPLE NO.	WIDTH (IN.)	THICK (IN.)	PEAK LOAD (LBS.)	STRENGTH Ksi	STRENGTH MPa.	DENSITY GMS./CC
1	0.2519	0.1279	248.0	67.71	466.8	
2	0.2526	0.1276	170.0	46.50	320.6	5.737
3	0.2514	0.1277	255.0	69.98	482.5	
4	0.2517	0.1277	255.0	69.89	481.9	
5	0.2521	0.1278	234.0	63.93	440.8	5.726
6	0.2532	0.1276	248.0	67.68	466.6	
7	0.2533	0.1273	270.0	74.00	510.2	
8	0.2531	0.1278	230.0	62.59	431.6	5.740
9	0.2423	0.1280	140.0	39.67	273.6	5.721
10	0.2506	0.1268	253.0	70.64	487.1	
11	0.2515	0.1273	256.0	70.66	487.2	
12	0.2529	0.1275	275.0	75.25	518.9	
13	0.2522	0.1276	275.0	75.34	519.5	5.722
14	0.2505	0.1273	255.0	70.67	487.3	
15	0.2523	0.1278	249.0	67.98	468.7	
			AVG.	66.17	456.22	
			STD. DEV.	9.77	67.35	

**** Weibull Analysis ****

A84-176 - NILSEN PSZ, GRADE MS

	Data Estimate	90 Percent Confidence Interval
Weibull Modulus =	5.21	3.89 < m < 6.53
Sigma Theta =	72.03	24.92 < Sig Theta < 208.22 ksi
(Assumed KV=1)		(Based on m= 5.21)

Correlation Coefficient = .8884

Interpolated Failure Levels		90 Percent Confidence Interval	
		Lower Bound	Upper Bound
Failure Probability	Fracture Strength	< Prob <	
.050	40.73	.017	.144
.100	46.76	.037	.254
.200	54.01	.082	.440
.300	59.10	.131	.595
.400	63.31	.184	.723
.500	67.13	.241	.825
.600	70.83	.304	.901
.700	74.64	.376	.954
.800	78.92	.462	.985
.900	84.54	.578	.998
.950	88.92	.665	****

A84-176 - NILSEN PSZ. GRADE MS

Failure Probability	Fracture Strength	Failure Probability	Fracture Strength
.063	39.67	.563	69.98
.125	46.50	.625	70.64
.188	62.59	.688	70.66
.250	63.93	.750	70.67
.313	67.68	.813	74.00
.375	67.71	.875	75.25
.438	67.98	.938	75.34
.500	69.89		

	Data Estimate	90 Percent Confidence Interval
Mean Strength =	66.17	61.57 < Mean < 70.76 ksi
Std. Deviation =	10.11	7.77 < Std. Dev. < 14.76 ksi

Coefficient of Variation = 15.28 %

NAME: THOMAS YOUNG DATE: 20-Aug-84

REF BOOK-PAGE F444-28

PROJECT: MEF TITLE: OXIDE BASED SYSTEMS

DATA SHEET NO. C-84-176-2

JOB NUMBER A84-176
TEST DES. IMMERSION DENSITY

MATERIAL: NILSEN PSZ MAT'L., GRADE MS MOR BARS
(6.05 GMS./CC THEO. DENSITY)

SAMPLE NO.	BULK DENSITY	APPARENT DENSITY	THEOR. DENSITY	APPARENT POROSITY	DRY WEIGHT	IMMERSED WEIGHT	TARE WEIGHT	SATURATED WEIGHT
1	5.721	5.721	94.56%	0.01%	6.3799	10.0800	4.8152	6.3800
2	5.737	5.737	94.82%	0.01%	6.3965	10.1012	4.8196	6.3966
3	5.723	5.723	94.60%	0.00%	6.3562	10.0660	4.8204	6.3562
4	5.733	5.733	94.77%	0.00%	6.3629	10.0728	4.8197	6.3629
5	5.726	5.726	94.64%	0.00%	6.3755	10.0822	4.8202	6.3755
6	5.740	5.740	94.88%	0.00%	6.4005	10.1050	4.8195	6.4005
7	5.741	5.742	94.90%	0.01%	6.3993	10.1036	4.8188	6.3994
8	5.740	5.741	94.88%	0.01%	6.4184	10.1196	4.8192	6.4185
9	5.721	5.724	94.56%	0.06%	6.3773	10.0824	4.8192	6.3780
10	5.736	5.738	94.80%	0.05%	6.2995	10.0206	4.8189	6.3000
11	5.736	5.736	94.80%	0.01%	6.3339	10.0484	4.8187	6.3340
12	5.719	5.719	94.53%	0.00%	6.3841	10.0860	4.8182	6.3841
13	5.722	5.725	94.57%	0.06%	6.3744	10.0785	4.8175	6.3751
14	5.739	5.741	94.85%	0.04%	6.3291	10.0436	4.8170	6.3295
15	5.726	5.736	94.64%	0.01%	6.3812	10.0833	4.8165	6.3813

RESEARCH LABORATORY NOTES THE CARBORUNDUM CO

NAME: THOMAS YOUNG DATE: 20-Aug-84

REF BOOK-PAGE F444-2

PROJECT: MEF TITLE: OXIDE BASED SYSTEMS

DATA SHEET NO. C-84-176-3

JOB NUMBER A84-176

MATERIAL: NILSEN PSZ MAT'L., GRADE MS MOR BARS

TEST MODE ELASTIC CONSTANTS FROM ULTRASONIC VELOCITY

SAMPLE NO.	DENSITY gms/cc	THICK (IN.)	tt microsec.	tl microsec	MU	G GPa	E GPa	E Mpsi
2	5.7370	0.1276	1.740	0.924	0.30	79.6	207.6	30.11
5	5.7260	0.1278	1.730	0.923	0.30	80.6	209.8	30.43
8	5.7400	0.1279	1.740	0.924	0.30	79.9	208.3	30.22
9	5.7210	0.1280	1.730	0.921	0.30	80.8	210.5	30.53
13	5.7220	0.1276	1.740	0.922	0.30	79.4	207.2	30.06

JOB NO. :A85-13

CHARACTERIZATION REPORT

TO : W. P. BINNIE

FROM : THOMAS YOUNG

DATE : 23-MAY-85
COPIES : S. SESHADRI
FILE

SAMPLE DESIGNATION : BARS NOS. 1 - 30

MATERIAL DESCRIPTION : HITACHI SYALON

NOTEBOOK REFS -- MAT'L :

DATA : F321-71
DISK : #24

RESULTS SUMMARY :
(COPIES OF NOTEBOOK DATA ATTACHED)

BULK DENSITY RANGE:

3.234 GM/CC TO 3.260 GM/CC

SONIC MODULUS RANGE:

40.92 Mpsi 282.1 GPa

TO

41.38 Mpsi 285.3 GPa

STRENGTH DATA:

SAMPLE	TEMP.	NO. OF SPEC	AVG KSI	STD. DEV. KSI	AVG. MPa	STD. DEV. MPa
NO. 1-15	23 C	15	98.94	17.84	682.22	122.97
NO. 16-30	525 C	15	89.59	11.27	617.73	77.71

WEIBULL ANALYSIS:
TESTED @ 23 C

WEIBULL MOD.- 4.38
SIGMA THETA - 109.02
CORR. COEF. - 0.92

WEIBULL ANALYSIS:
TESTED @ 525 C

WEIBULL MOD.- 7.86
SIGMA THETA - 94.86
CORR. COEF. - 0.98

JOB NO. :A85-13

CHARACTERIZATION REPORT

TO : W. P. BINNIE

FROM : THOMAS YOUNG

DATE : 23-MAY-85
COPIES : S. SESHADRI
FILE

SAMPLE DESIGNATION : BARS NOS. 1 - 30

MATERIAL DESCRIPTION : HITACHI SYALON

NOTEBOOK REFS -- MAT'L :

DATA : F321-71
DISK : #24

RESULTS SUMMARY :
(COPIES OF NOTEBOOK DATA ATTACHED)

INDENTATION FRACTURE TOUGHNESS:

SAMPLE	DENSITY GMS/CC	YOUNGS MODULUS Mpsi	HARDNESS GPa AVG.	HARDNESS GPa STD. DEV.	TOUGHNESS, MPa.SQRT(M) AVG.	TOUGHNESS, MPa.SQRT(M) STD. DEV.
4	3.238	41.05	14.09	0.23	5.285	0.072
9	3.252	40.92	14.02	0.68	5.425	0.121
14	3.260	41.38	14.19	0.22	5.178	0.105

** SAMPLES SUBMITTED FOR FAILURE ANALYSIS **

NAME: STEVE LACKI/RC DATE: 23-APR-85

REF BOOK-PAGE F312-71
DISK NO. 22

PROJECT: MEZ TITLE: SERV-TACOM-XP-489-SES

DATA SHEET NO. C-85-13-1

JOB NUMBER A85-13
TEST DES. IMMERSION DENSITY

MATERIAL: HITACHI SYALON

SAMPLE NO.	BULK DENSITY	APPARENT DENSITY	THEOR. DENSITY	APPARENT POROSITY	DRY WEIGHT	IMMERSED WEIGHT	TARE WEIGHT	SATURATED WEIGHT
2	3.257	3.258	99.91%	0.01%	3.1038	6.9126	4.7616	3.1039
4	3.238	3.239	99.32%	0.03%	3.1729	6.9572	4.7639	3.1732
6	3.250	3.251	99.70%	0.02%	3.1188	6.9216	4.7622	3.1190
9	3.252	3.253	99.76%	0.02%	3.1294	6.9314	4.7640	3.1296
12	3.234	3.236	99.21%	0.04%	3.2059	6.9796	4.7645	3.2063
14	3.260	3.261	100.00%	0.03%	3.0836	6.9020	4.7640	3.0839

NAME: STEVE LACKI/RC DATE: 23-APR-85

REF BOOK-PAGE F312-71
DISK NO. 22

PROJECT: MEZ TITLE: SERV-TACOM-XP-489-SES
DATA SHEET NO: C-85-13-2

JOB NUMBER: A85-13
TEST DES: RESONANT MODULUS MEASUREMENTS - FLATWISE

MATERIAL: HITACHI SYALON

SAMPLE No	LENGTH in	WIDTH in	MASS gms	THICK in	FLEX FREQ Hz	YOUNG'S MODULUS Mpsi	GPa	POISSON'S RATIO Assd
2	2.0030	0.2523	3.1038	0.1165	10938	41.38	285.3	0.240
4	1.9990	0.2505	3.1729	0.1199	11235	41.05	283.0	0.240
6	1.9990	0.2505	3.1188	0.1182	11088	40.99	282.6	0.240
9	2.0030	0.2508	3.1294	0.1181	11020	40.92	282.1	0.240
12	2.0040	0.2526	3.2059	0.1199	11204	41.21	284.1	0.240
14	1.9990	0.2472	3.0836	0.1178	11074	41.38	285.3	0.240

NAME: STEVE LACKI/PC DATE: 23-APR-85

REF BOOK-PAGE #312-71
DISK NO. 22

PROJECT: MEZ TITLE: SERV-TACOM-X0-489-563

JOB NUMBER A85-13 DATA SHEET NO. C-85-13-3A

MATERIAL: HITACHI SYALON

TEST MODE 4-PT. FLEX TEST OUTER SPAN (IN) : 1.50
INNER SPAN (IN) : 0.75

CROSS HEAD SPEED 0.02 IN./MIN.
CHART SPEED 150 CM./HR. TEST TEMPERATURE: 23C
TEST DATE 19-APR-85

SAMPLE NO.	WIDTH (IN.)	THICK (IN.)	PEAK LOAD (LBS.)	STRENGTH Ksi	MPa.	DENSITY GMS./CC
1	0.2502	0.1162	302.0	100.57	693.4	
2	0.2523	0.1165	351.0	115.32	795.1	3.257
3	0.2524	0.1186	411.0	130.24	898.0	
4	0.2505	0.1199	158.0	49.36	340.3	3.238
5	0.2493	0.1199	273.0	85.69	590.9	
6	0.2505	0.1182	296.0	95.15	656.0	3.250
7	0.2509	0.1187	337.0	107.25	739.5	
8	0.2477	0.1197	294.0	93.19	642.6	
9	0.2508	0.1181	318.0	102.27	705.2	3.252
10	0.2480	0.1172	285.0	94.12	649.0	
11	0.2509	0.1184	292.0	93.40	644.0	
12	0.2526	0.1199	378.0	117.10	807.4	3.234
13	0.2508	0.1189	333.0	105.66	728.5	
14	0.2472	0.1178	336.0	110.19	759.8	3.260
15	0.2495	0.1197	269.0	84.65	583.7	
			AVG.	98.94	682.22	
			STD. DEV.	17.84	122.97	

NAME: STEVE LACKI/RC DATE: 23-APR-85

REF BOOK-PAGE F312-71
DISK NO. 22

PROJECT: MEZ TITLE: SERV-TACOM-XP-489-SES

JOB NUMBER A85-13 DATA SHEET NO. C-85-13-3B

MATERIAL: HITACHI SYALON

TEST MODE 4-PT. FLEX TEST OUTER SPAN (IN) : 1.50
INNER SPAN (IN) : 0.75

CROSS HEAD SPEED 0.02 IN./MIN.
CHART SPEED 150 CM./HR. TEST TEMPERATURE: 525 C
TEST DATE 19-APR-85

SAMPLE NO.	WIDTH (IN.)	THICK (IN.)	PEAK LOAD (LBS.)	STRENGTH Ksi	MPa.	DENSITY GMS./CC
16	0.2589	0.1199	283.0	85.54	589.8	
17	0.2446	0.1194	262.0	84.53	582.8	
18	0.2510	0.1198	321.0	100.25	691.2	
19	0.2511	0.1200	269.0	83.69	577.1	
20	0.2461	0.1192	302.0	97.16	669.9	
21	0.2511	0.1197	225.0	70.36	485.1	
22	0.2570	0.1200	266.0	80.86	557.5	
23	0.2571	0.1189	275.0	85.12	586.9	
24	0.2447	0.1199	341.0	109.05	751.9	
25	0.2480	0.1201	230.0	72.33	498.7	
26	0.2554	0.1193	257.0	79.54	548.4	
27	0.2448	0.1188	291.0	94.75	653.3	
28	0.2621	0.1200	342.0	101.94	702.9	
29	0.2458	0.1196	296.0	94.71	653.0	
30	0.2500	0.1202	334.0	104.03	717.3	
			AVG.	89.59	617.73	
			STD. DEV.	11.27	77.71	

**** Weibull Analysis ****

A85-13 HITACHI SYALON TESTED AT ROOM TEMP.

	Data Estimate	90 Percent Confidence Interval
Weibull Modulus =	4.38	3.44 (m (5.32
Sigma Theta =	109.02	40.89 (Sig Theta(290.66 ksi
(Assumed KV=1)		(Based on m= 4.38)
Correlation Coefficient = .9167		

Interpolated Failure Levels		90 Percent Confidence Interval	
		Lower Bound	Upper Bound
Failure Probability	Fracture Strength	(Prob (	
.050	55.33	.019	.125
.100	65.21	.043	.225
.200	77.40	.093	.400
.300	86.15	.147	.551
.400	93.52	.205	.680
.500	100.27	.267	.787
.600	106.86	.336	.872
.700	113.74	.413	.934
.800	121.53	.505	.975
.900	131.89	.626	.995
.950	140.06	.714	.999

A85-13 HITACHI SYALON TESTED AT ROOM TEMP.

Failure Probability	Fracture Strength	Failure Probability	Fracture Strength
.063	49.36	.563	102.27
.125	84.65	.625	105.66
.188	85.69	.688	107.25
.250	93.19	.750	110.19
.313	93.40	.813	115.32
.375	94.12	.875	117.10
.438	95.15	.938	130.24
.500	100.57		

	Data Estimate	90 Percent Confidence Interval
Mean Strength =	98.94	90.55 < Mean < 107.34 ksi
Std. Deviation =	18.46	14.19 < Std. Dev. < 26.95 ksi

Coefficient of Variation = 18.66 %

**** Weibull Analysis ****

A85-13 HITACHI SYALON TESTED AT 525 C

	Data Estimate	90 Percent Confidence Interval
Weibull Modulus =	7.86	7.11 (m (8.61
Sigma Theta =	94.86	61.86 (Sig Theta(145.49 ksi
(Assumed KV=1)		(Based on m= 7.86)
Correlation Coefficient = .9817		

Interpolated Failure Levels		90 Percent Confidence Interval	
		Lower Bound (Prob (	Upper Bound
Failure Probability	Fracture Strength		
.050	65.01	.032	.077
.100	71.25	.067	.148
.200	78.38	.140	.292
.300	83.20	.215	.408
.400	87.09	.294	.527
.500	90.54	.377	.638
.600	93.82	.464	.740
.700	97.13	.558	.830
.800	100.79	.662	.908
.900	105.48	.785	.968
.950	109.08	.863	.989

A85-13 HITACHI SYALON TESTED AT 525 C

Failure Probability	Fracture Strength	Failure Probability	Fracture Strength
.063	70.36	.563	94.71
.125	72.33	.625	94.75
.188	79.54	.688	97.16
.250	80.86	.750	100.25
.313	83.69	.813	101.94
.375	84.53	.875	104.03
.438	85.12	.938	109.05
.500	85.54		

	Data Estimate	90 Percent Confidence Interval
Mean Strength =	89.59	84.29 < Mean < 94.89 ksi
Std. Deviation =	11.67	8.97 < Std. Dev. < 17.03 ksi

Coefficient of Variation = 13.02 %

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APPENDIX I

PREPARATIONS AND NDE OF SPECIMENS FOR STUDY OF ACOUSTO-OPTIC EFFECTS

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CARBORUNDUM

Carborundum
Resistant Materials Company
Advanced Materials Division
P.O. Box 832
Niagara Falls, New York 14302

Telephone 716 278-6103
Telex: 91-383

October 24, 1983

Richard Silberglitt
DHR, Inc.
6858 Old Dominion Drive
McLean, VA 22101

Dear Rich:

Enclosed is a report prepared for DHR, summarizing Carborundum's data on the NDE characterization of ten sintered alpha silicon carbide specimens. The specimens have been sent to your attention separately for DHR's research investigation using the non-specular reflection technique.

If you have specific questions regarding the data contained in the report, please feel free to contact Dr. Srinivasan directly.

Sincerely,

James MacBeth

James W. MacBeth
Business Development Manager
Advanced Materials Division

JWM/lbr

cc: M. Srinivasan
R. Storm

Preparation and NDE of specimens for dhr, Inc. study of nonspecular reflection effects

W. P. Rogers

M. Srinivasan

Advanced Materials Division

Engineering Materials Sector

Sohio Chemicals and Industrial Products Co.

October 1983

Sample Preparation

Ten specimens of Carborundum Hexoloy SA sintered alpha silicon carbide were prepared to explore the application of a nonspecular reflection effects technique as a nondestructive evaluation method. In order to provide a variety of specimen types, three parameters were varied: specimen size and shape, surface condition, and surface flaw size. Surface flaws are either "natural" processing - related pores and machining cracks or 'artificial' Vicker's indentation flaws. The Vicker's indentation provides surface flaws of known size and shape. Table I summarizes this information for the ten specimens. Figure 1 shows the location of the indentations on the specimens' surfaces.

Table 1 Silicon Carbide Specimens

10#	Size & Shape	Surface Condition	Type of Flaw
1	1/4 x 1/8 x 2" bar	as-fired	7, 3, 5 kg indentation
2	1/4 x 1/8 x 2" bar	machined	7, 3, 5 kg indentation
3	1/4 x 1/8 x 2" bar	polished	7, 3, 5 kg indentation
4	1/4 x 1/8 x 2" bar	as-fired	natural
5	1/4 x 1/8 x 2" bar	machined	natural
6	1/4 x 1/8 x 2" bar	polished	natural
7	1/4 x 1/8 x 2" bar	machined	high porosity
8	1/4 x 1/8 x 2" bar	polished	high porosity
9	2 x 2 x 1/4" plate	polished	2, 3, 4, 5, 6, 7, 8, 10 kg
10	2 1/2" diam. seal	as-fired	natural

SAW Ultrasonic Testing

A surface acoustic wave (SAW) technique was used to inspect the specimens for microscopic surface defects. The technique utilizes a high frequency ultrasonic testing system shown schematicly in figures 2 and 3. It is a custom-made 40 MHZ pulse-echo ultrasonic system with C-scan and A-scan capability. For surface wave testing the transducer head (transducer and preamp) is turned to a critical (Rayleigh) angle relative to the test piece. The transducer is scanned over the surface and a two dimensional map of flaw location known as a C-scan, is obtained on the x-y plotter.

The amplitude of the ultrasonic pulse reflected by a surface flaw is viewed on the oscilloscope (A-scan). Some of the relevant ultrasonic parameters for alpha silicon carbide are listed in the appendix. Results of SAW ultrasonic testing are given in the following figures.

Figure 4 shows the C-scan of four test bars with as-sintered surfaces. Sample 1 contains three indentations, however, only the 7kg load flaws was detected. The other indications correspond to natural surface or subsurface pores.

Figure 5 is a C-scan of six test bars with as-machined or polished surfaces. The three indentation cracks in samples 2 and 3 show up very clearly, in addition to the natural pores. The C-scans of the as-machined bars (2, 5, and 7) are very similar to the scans of the polished bars (3, 6, and 8), indicating that surface roughness does not greatly affect the sensitivity of detection. Test bars 7 and 8 contain many small pores due to the fabrication process. The difference in microstructure between the high and low porosity samples is shown in figure 6.

Figure 7 shows a C-scan of the polished face of a 2 x 2 in. plate containing eight Vickers indentation cracks. All of the indentations were detected except the 2kg load. A number of natural pores are also evident. Micrographs of the indentations and their corresponding ultrasonic A-scans are shown in figures 8-13. Note that the amplitude of the reflected signal decreases as the indentation crack size decreases. Figure 14 shows a micrograph of a very large natural pore on the sample surface.

X-ray Radiography

A Magnaflux microfocus X-ray facility was used to detect internal defects in the specimens. The exposure conditions used were: Type M film, 28 in. film-focal spot distance, 40kv, 0.7 MA, 15 min. Using the best techniques available, no internal or surface defects were detected. The sensitivity of the X-ray method is at best 2% of the thickness of a specimen. In a 1/8 in. thick test bar the smallest detectable defect would be about 70 mm. However, seeing a pore indication of this size on a film is not possible by the unaided eye. Furthermore, cracks such as those resulting from Vicker's indentation can not be detected with radiography since they have very small width. At present, radiographic testing can not provide the degree of sensitivity that high frequency ultransoics can.

Appendix

Ultrasonic Velocity and elastic constants of sintered alpha silicon carbide

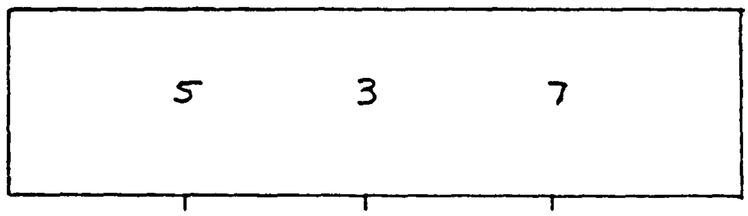
Density	Ultrasonic Velocity		Young's modulus	Poissons ratio
	long	shear		
(g/cc)	(mm/μs)	(mm/μs)	(GPa)	
3.14	11.94	7.66	424	0.15
3.08	11.67	7.47	396	0.15

Rayleigh angle in water:

$$\theta = \sin^{-1} \frac{V\ water}{V\ shear} = 11^{\circ}$$

Figure 1 Map of Vicker's indentations, load in kg.

Samples 1, 2, 3



Sample 9

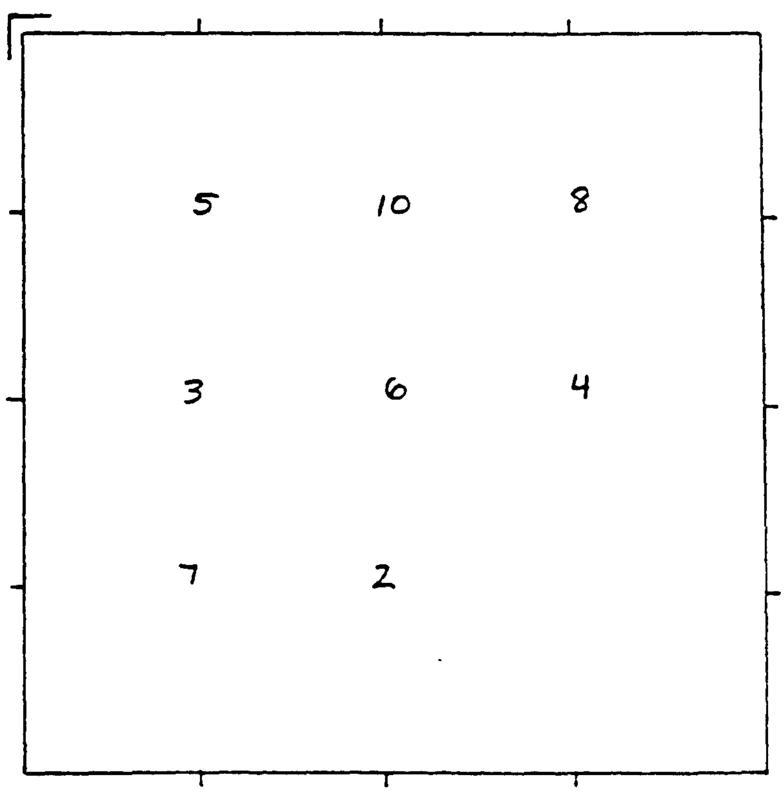


Figure 2.

Schematic Diagram of Scanning Ultrasonic System

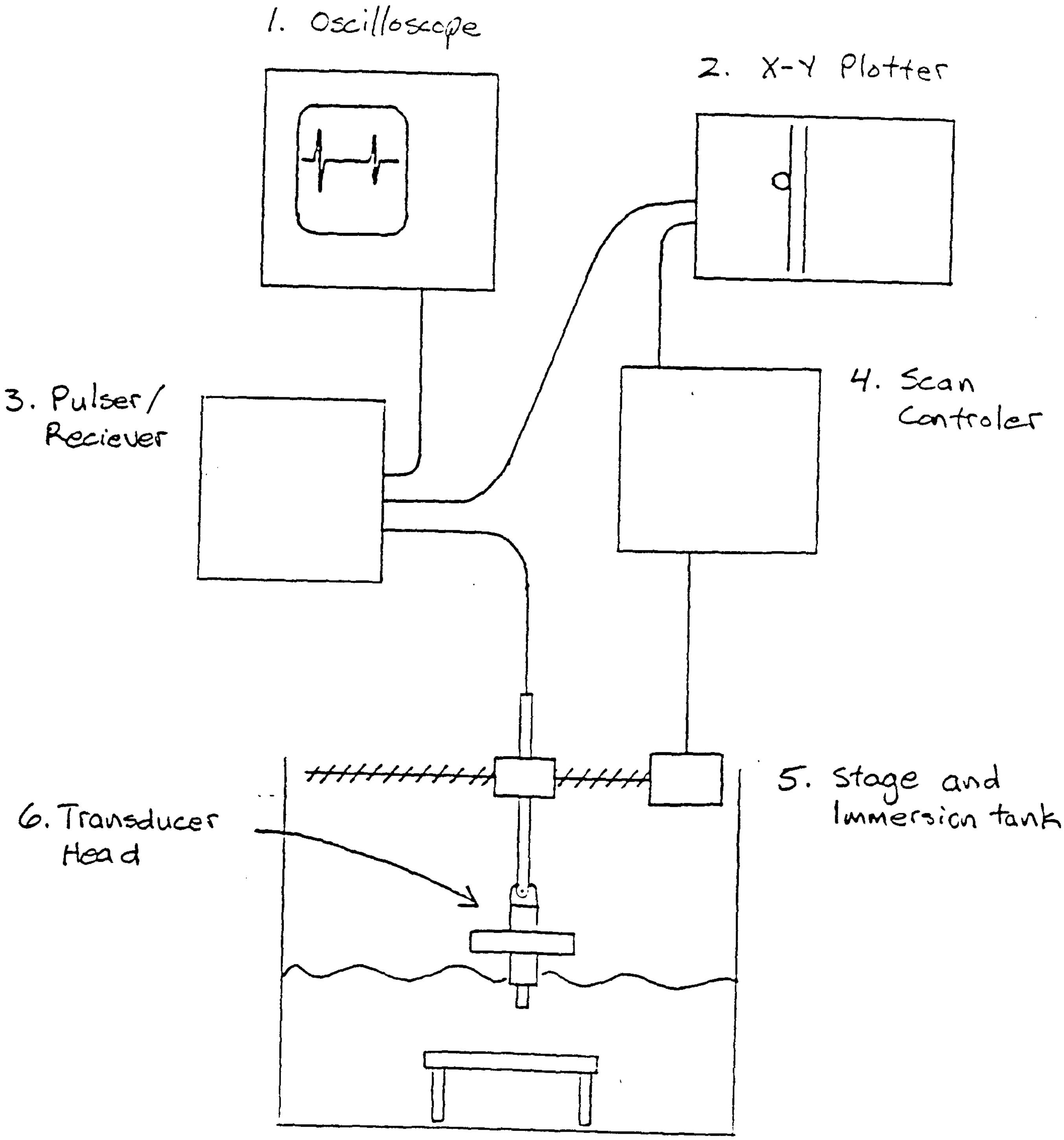
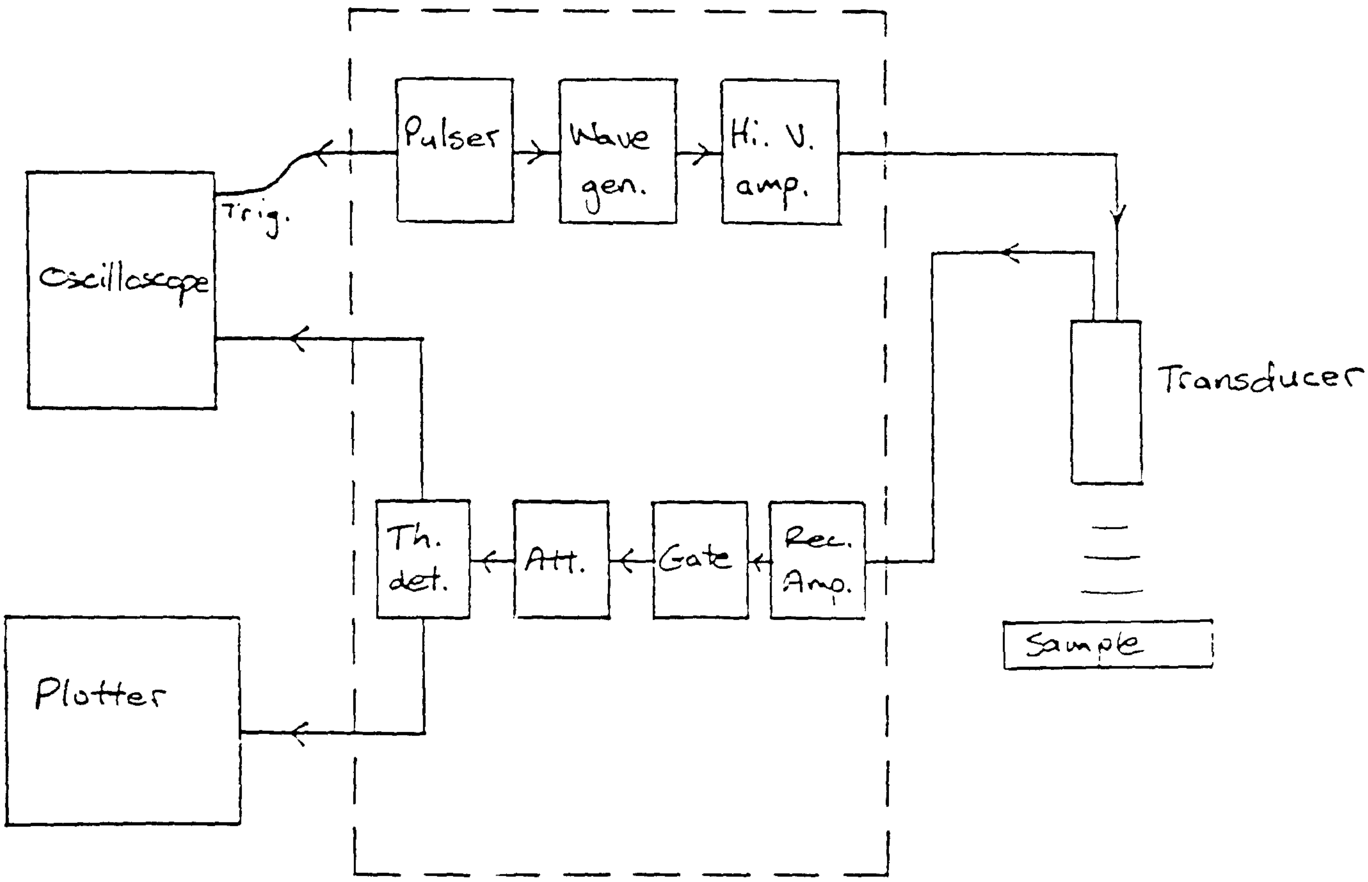


Figure 3.

Schematic Diagram of Pulser/Reciever Section



MOR BARS [illegible]

AS-FIRED SURFACES

SAW ULTRASONIC TESTING

C-SCAN

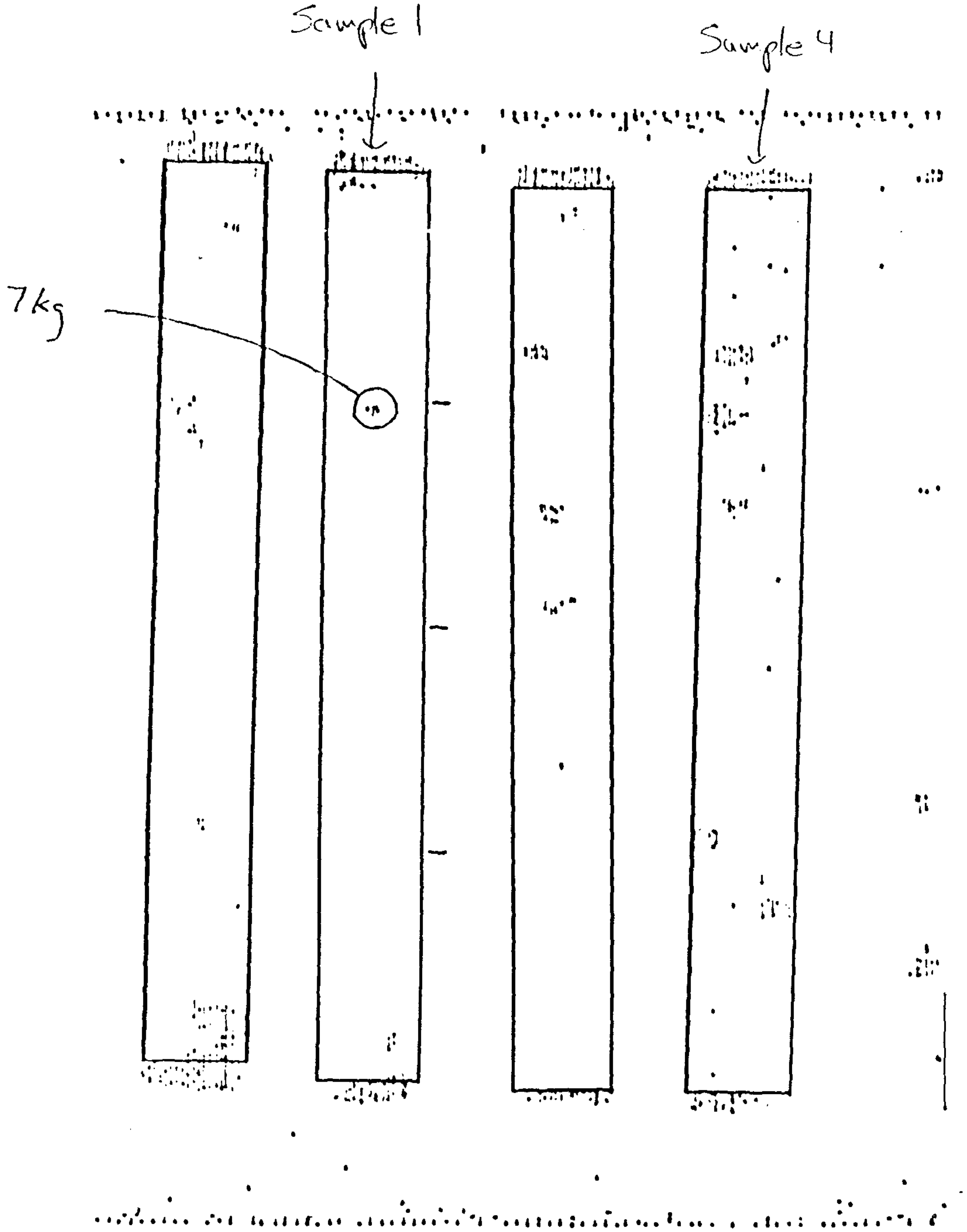


Figure 4.

Figure 5.

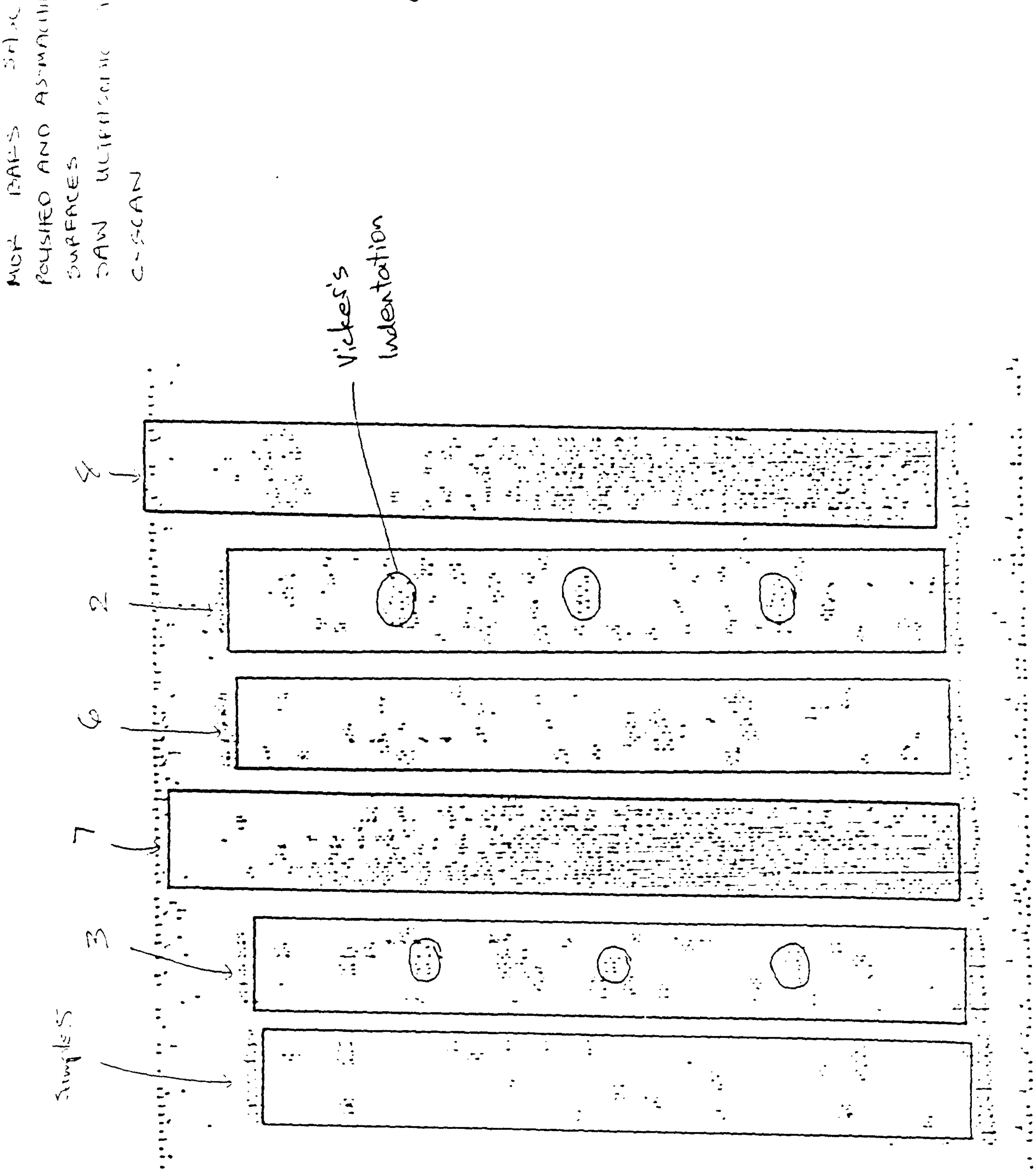
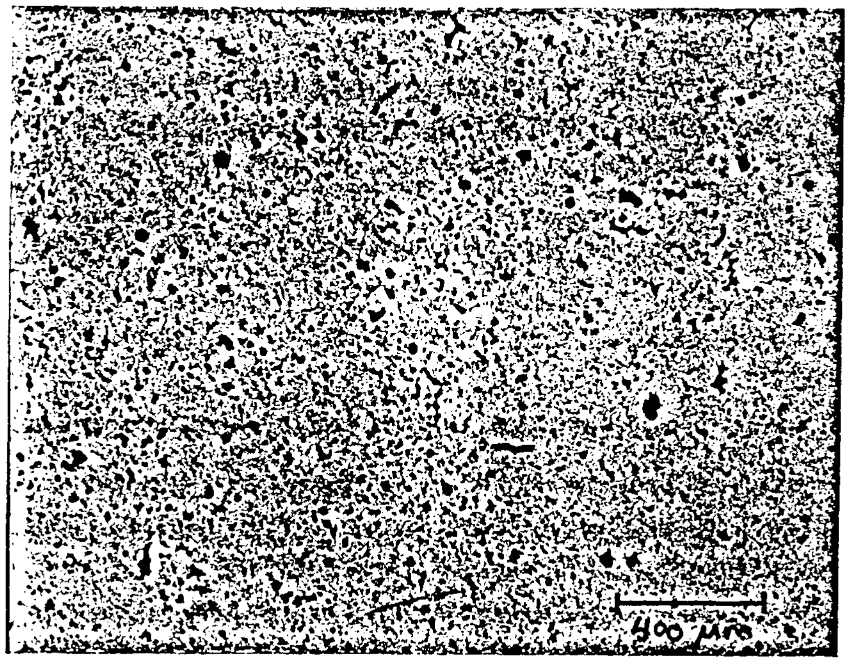

MOR BARS
POLISHED AND AS-MACHINED
SURFACES
C-SCAN
Samples
3
7
6
2
4
Vicker's
Indentation

Figure 6. Micrographs of sample 8 with high porosity (top) and sample 6 with low porosity (bottom).



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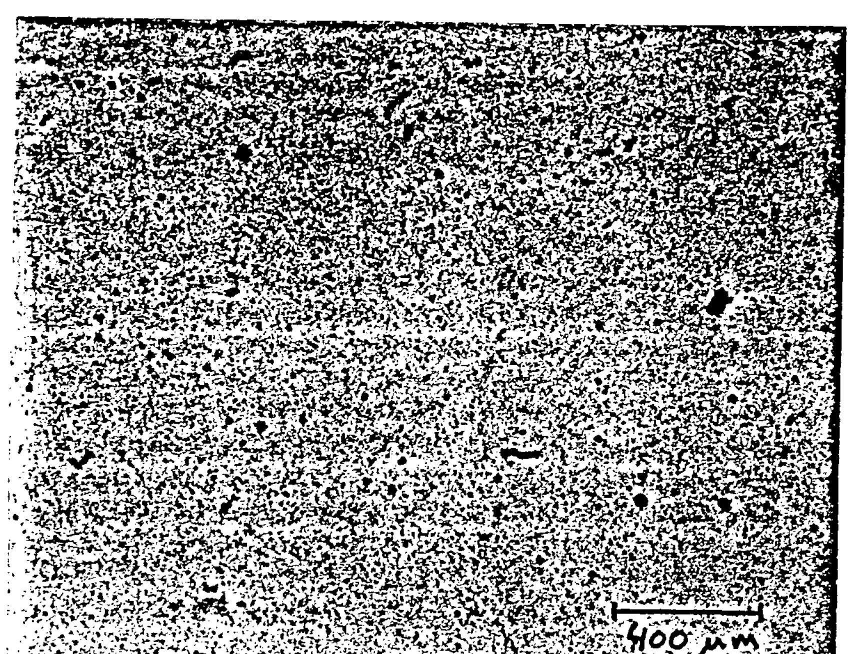


50X

Figure 7.

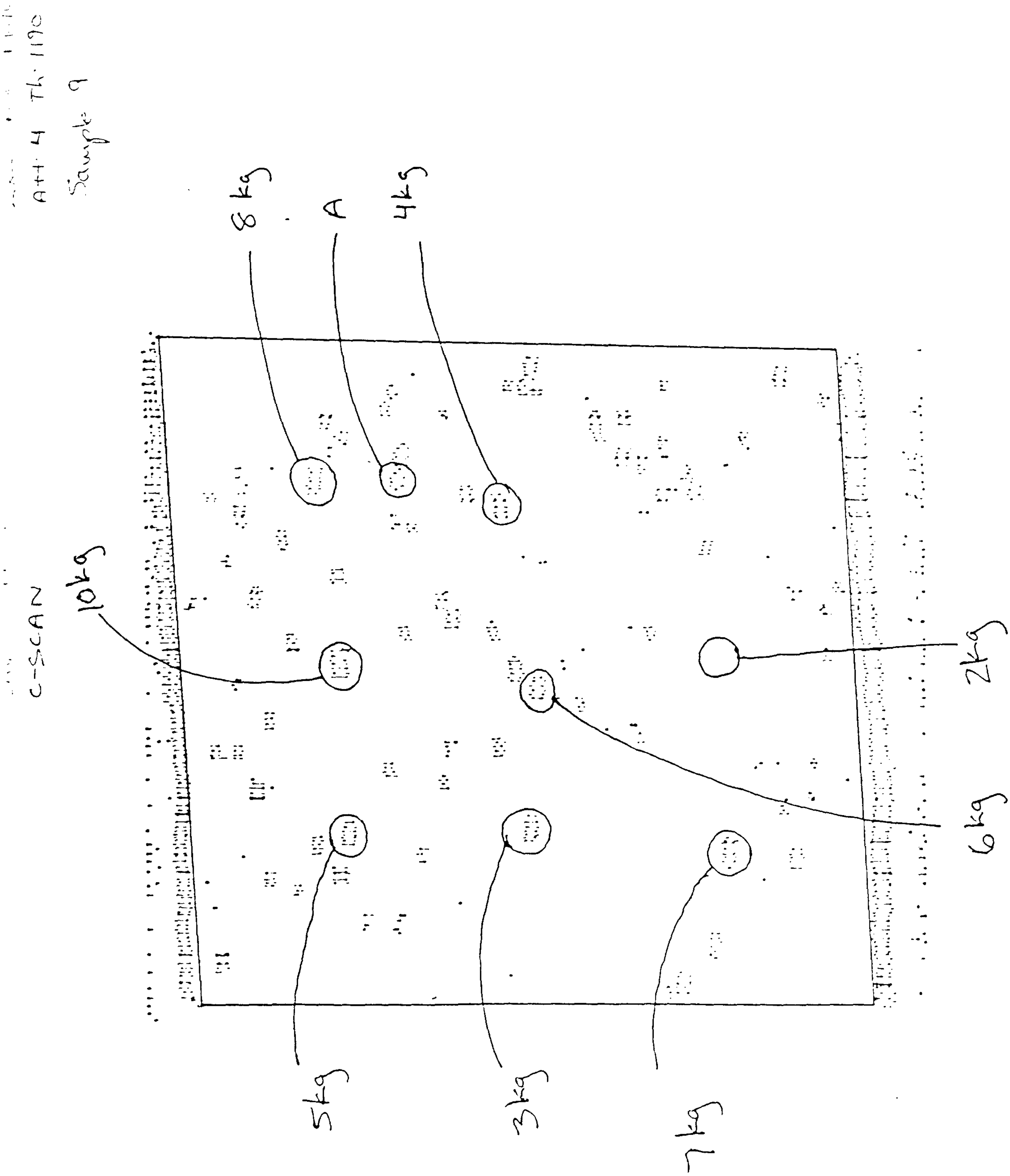
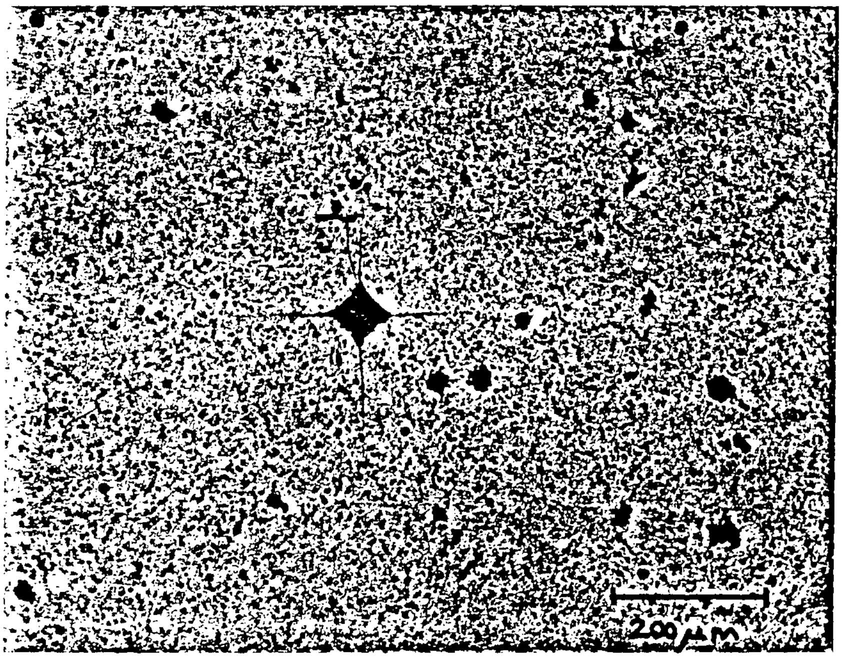
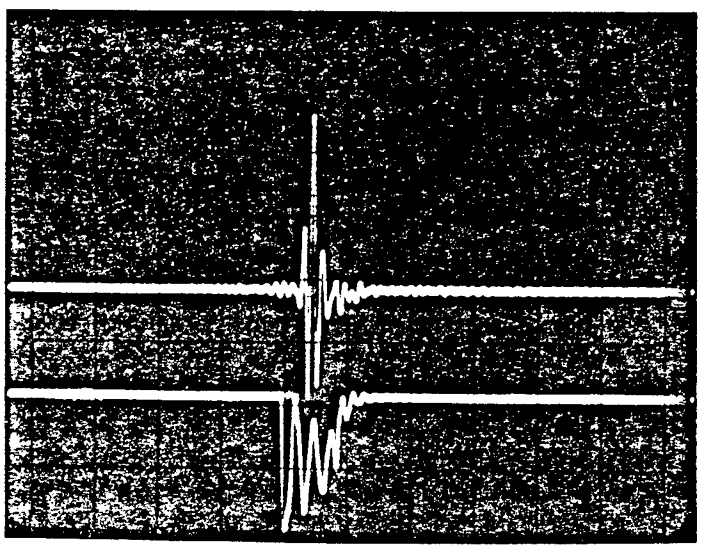


Figure 8. Micrograph of Sample 9 10kg Vicker's indentation and ultrasonic A-scan.



100X

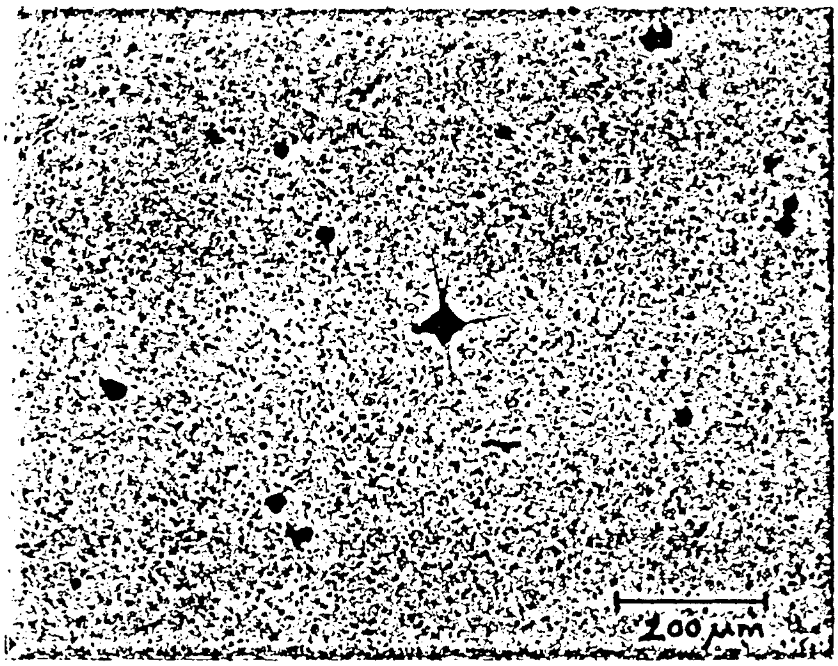


Amp. 280 mV

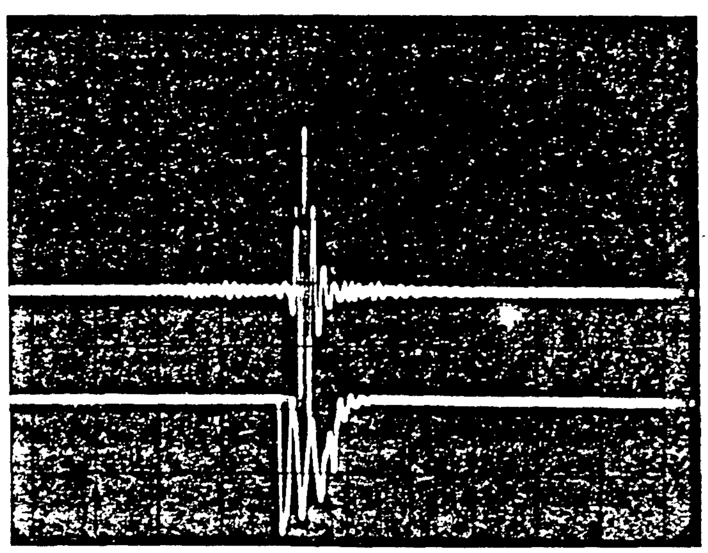
50 mV

.2 μs

Figure 9. Sample 9, 8kg indentation micrograph and A-scan.



50X

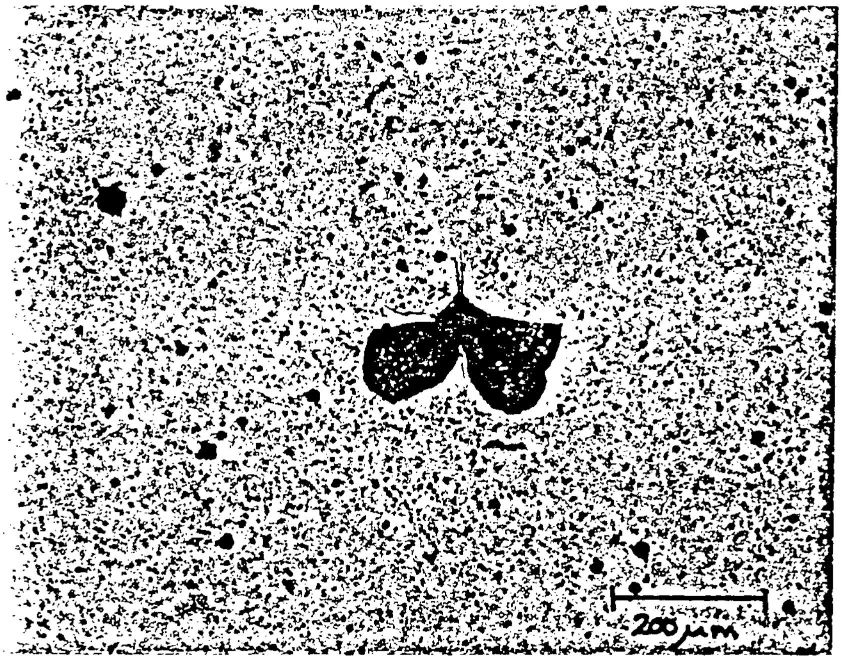


Amp. 260 mV

50 mV

.2 µs

Figure 10. Sample 9, 7kg indentation micrograph and A-scan.



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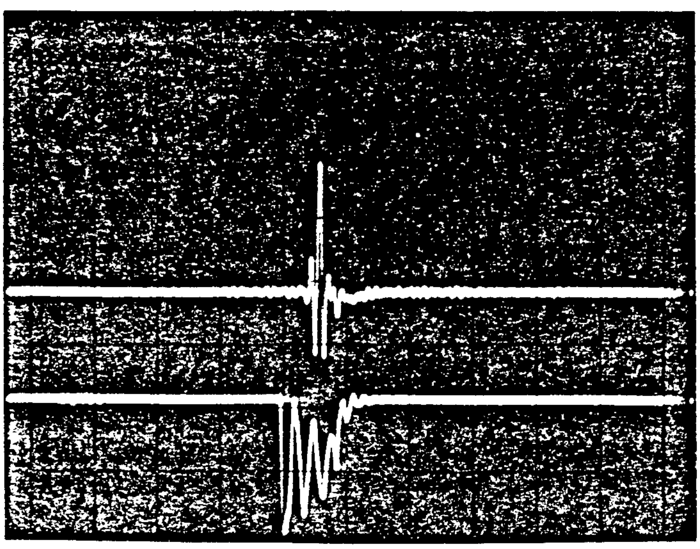
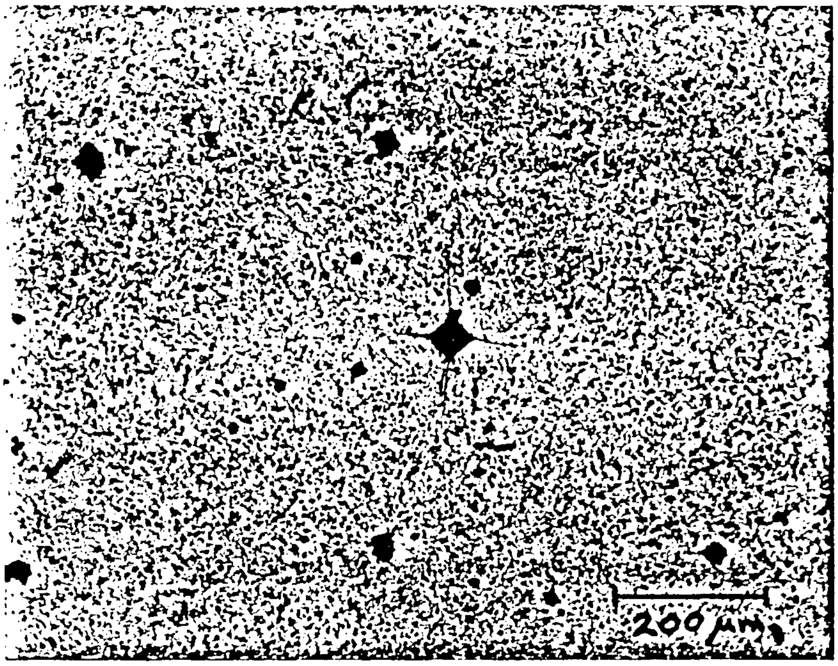


Amp. 200mV

50mV

.2μs

Figure 11. Sample 9, 6kg indentation micrograph and A-scan.



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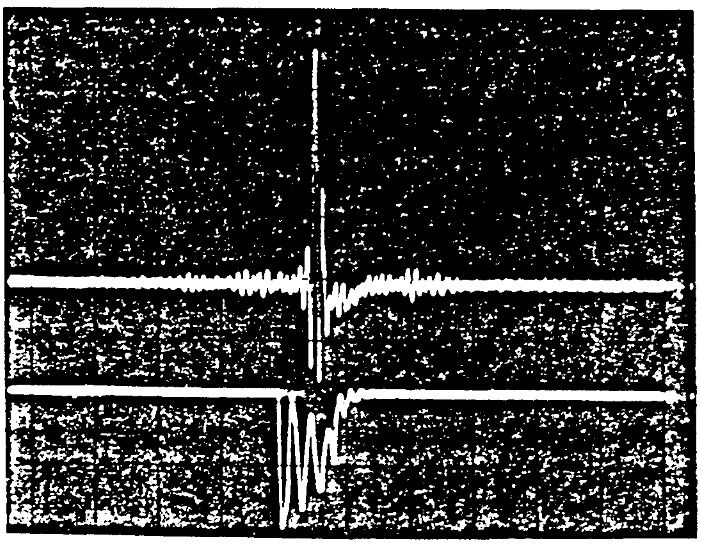
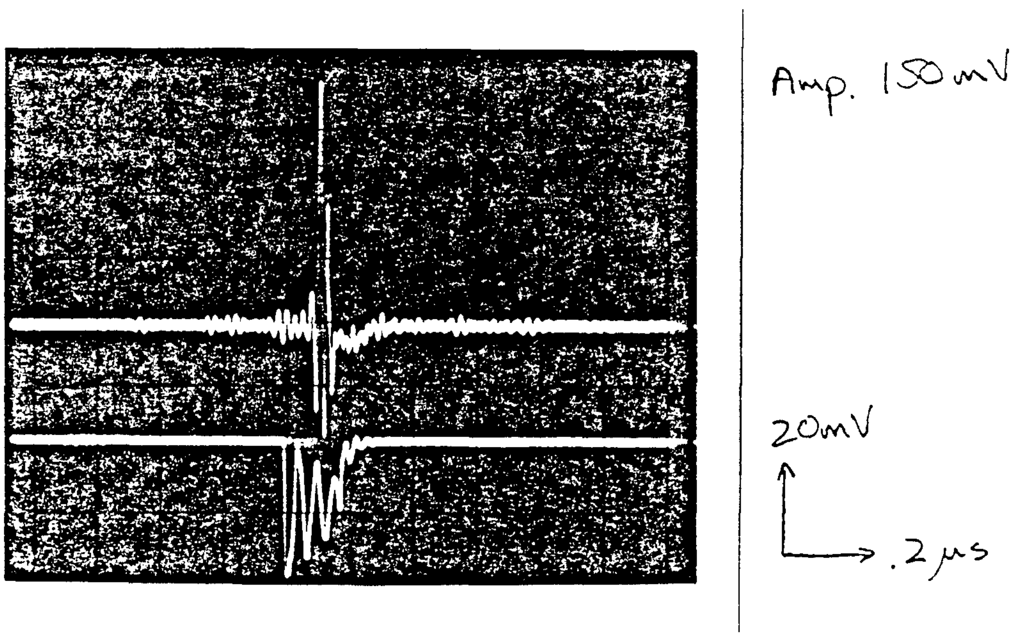


Amp. 140mV

20mV

.2μs

Figure 12. Sample 9, 5kg indentation A-scan (top) and natural flaw A-scan (bottom), marked flaw A on C-scan in figure 7.



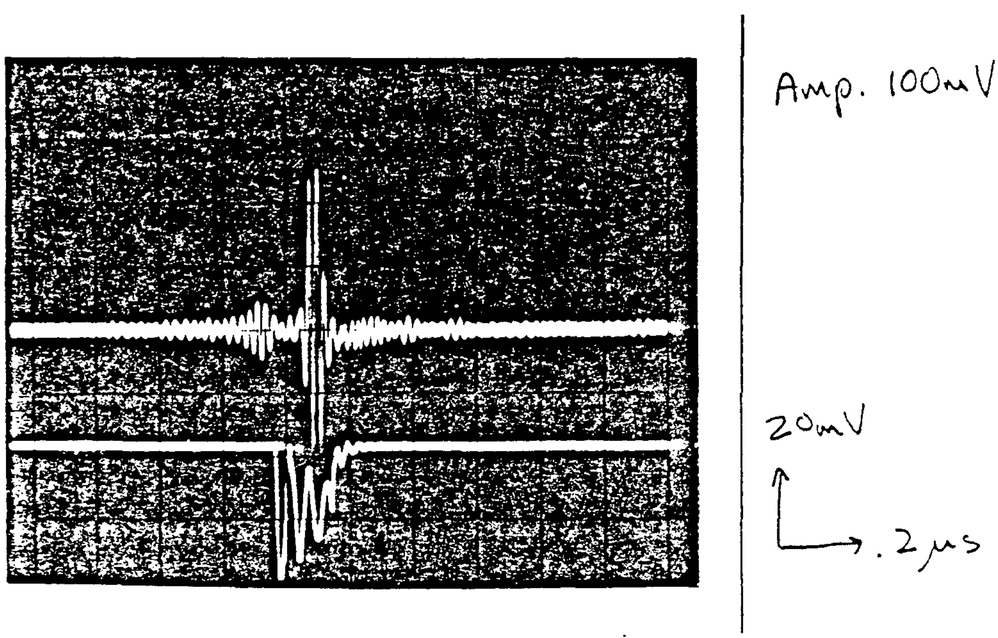
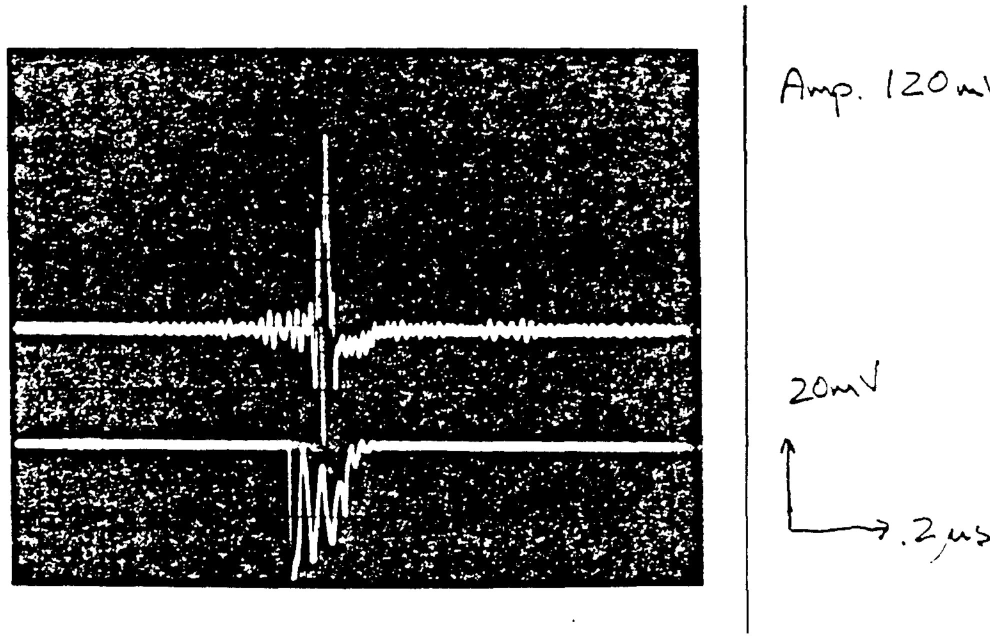


Figure 13. Sample 9, 3kg indentation A-scan (top), and 4kg incentation (bottom).



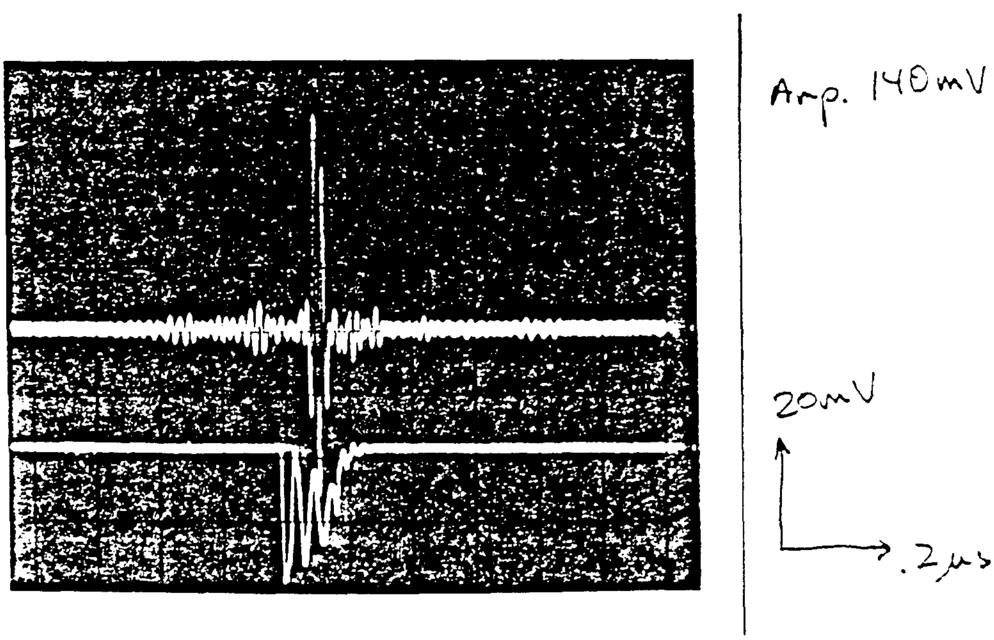
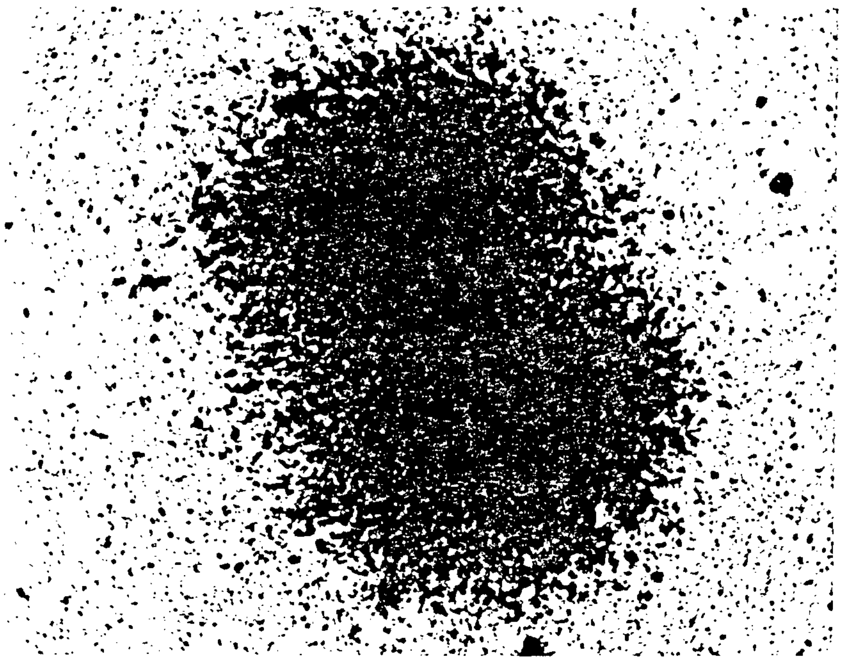


Figure 14. Sample 9, very large natural surface pore micrograph.



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